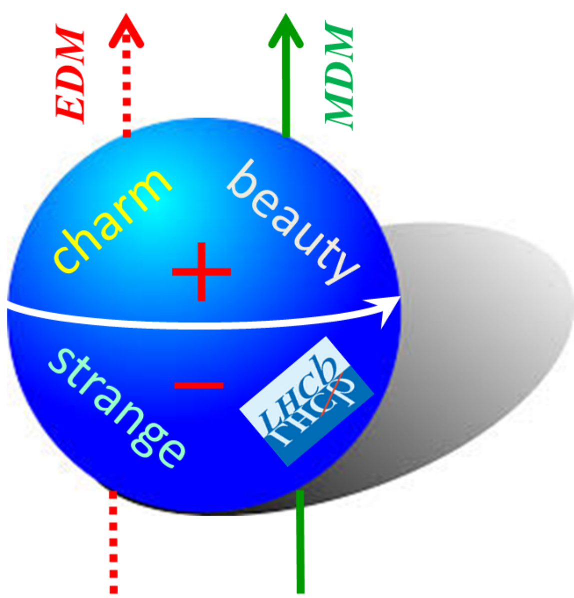
Baryon EDM and MDM measurements using bent crystals in LHCb



European Research Council
Established by the European Commission

Nicola Neri
INFN Sezione di Milano

Workshop on bent crystals
Ferrara, 13 February 2018

Outline

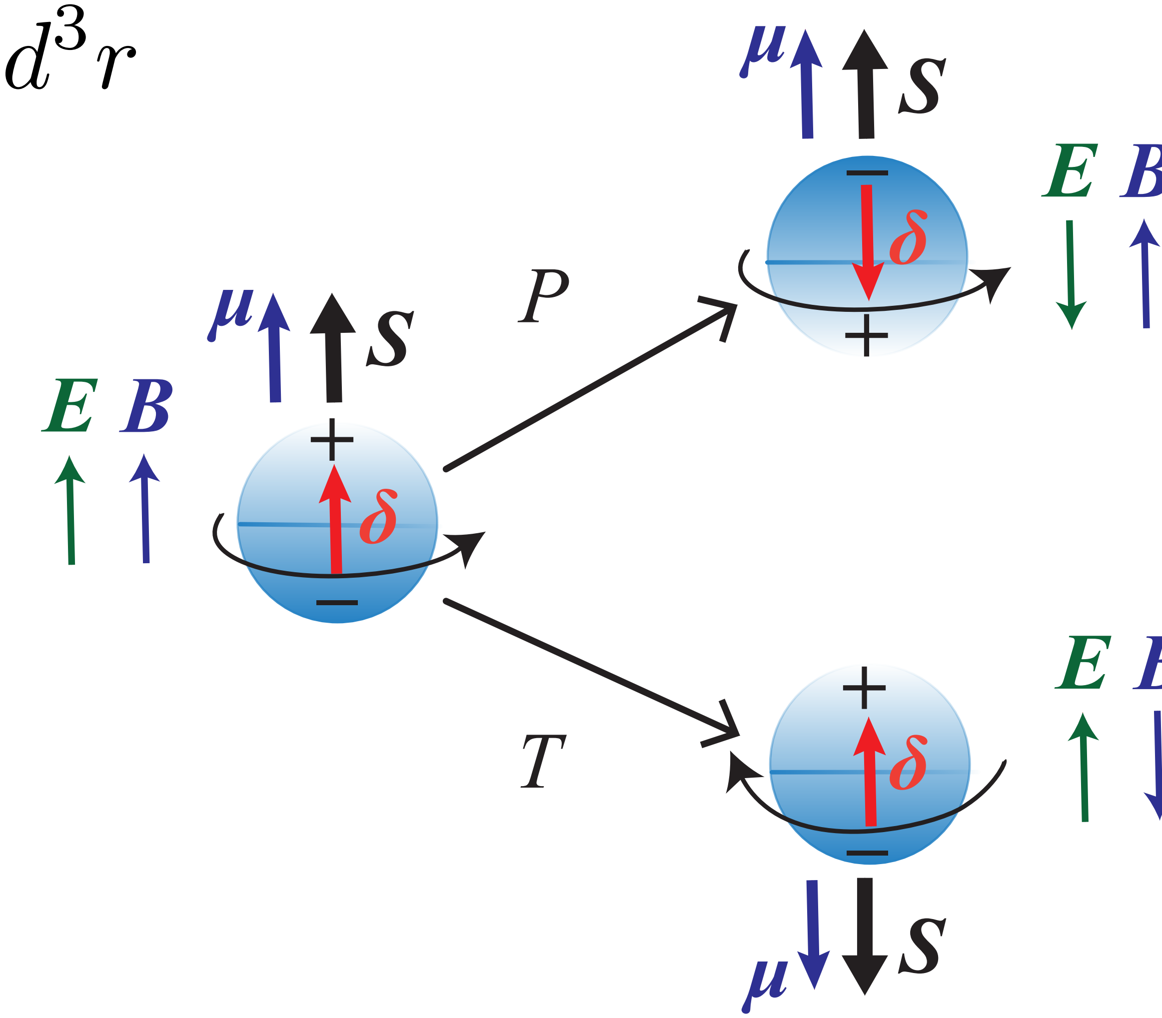
- EDM as a probe for new physics
- Experimental method
- Simulation studies
- Crystal optimisation
- Operational mode and timeline
- Summary

Electric dipole moment (EDM)

- Definition $\boldsymbol{\delta} = \int \mathbf{r}\rho(\mathbf{r})d^3r$

- Quantum systems

$$\boldsymbol{\delta} = d\mu_N \frac{\boldsymbol{S}}{2} \qquad \boldsymbol{\mu} = g\mu_N \frac{\boldsymbol{S}}{2}$$



- Hamiltonian

$$H = -\boldsymbol{\delta}\cdot\boldsymbol{E} - \boldsymbol{\mu}\cdot\boldsymbol{B}$$

Time reversal, parity: $d\mu_N \frac{\boldsymbol{S}}{2}\cdot\boldsymbol{E} \xrightarrow{T,P} -d\mu_N \frac{\boldsymbol{S}}{2}\cdot\boldsymbol{E}$

The EDM violates *T* and *P* and via *CPT* theorem, violates *CP*

Baryon EDM - Effective Lagrangian

- EDM coupling: $\mathcal{L}^{\mathrm{EDM}} = -\frac{i}{2}\delta\bar{\psi}\sigma^{\mu\nu}\gamma_5\psi F_{\mu\nu}$

- CP-odd flavour diagonal effective $\mathcal{L}$ (scale 1 GeV)

$$\mathcal{L}_{\mathrm{eff}}^{\not P \not T} = -\bar{\theta}\frac{g^2}{64\pi^2}\varepsilon^{\mu\nu\alpha\beta}G^a_{\mu\nu}G^a_{\alpha\beta}$$ θ-QCD term

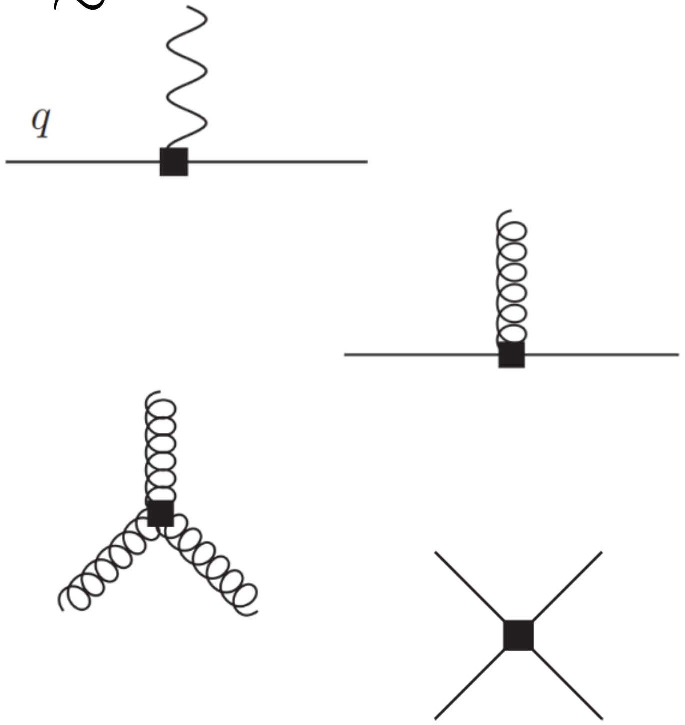
$\theta \lesssim 10^{-10}$ from nEDM

$$-\frac{1}{2}\sum_{q=u,d\ \mathbf{s,c}}(\delta_q\bar{q}i\sigma^{\mu\nu}\gamma_5 qF_{\mu\nu}$$ qEDM

$$+\tilde{\delta}_q\bar{q}i\sigma^{\mu\nu}\gamma_5 t_a qG^a_{\mu\nu})$$ qCEDM

$$+\frac{d_W}{6}f_{abc}\varepsilon^{\mu\nu\alpha\beta}G^a_{\alpha\beta}G^b_{\mu\rho}G^{c\rho}_{\nu}$$ Weinberg op.

$$+\sum_{i,j,k,l=u,d\ \mathbf{s,c}}C_{ijkl}\bar{q}_i\Gamma q_j\bar{q}_k\Gamma' q_l$$ 4q op.



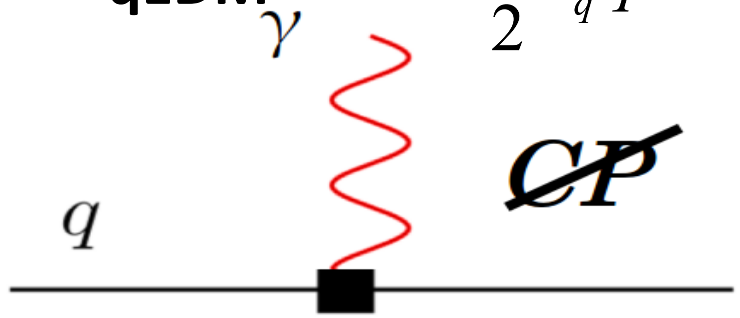
- Negligibly small contribution from SM

- Background free search for new physics

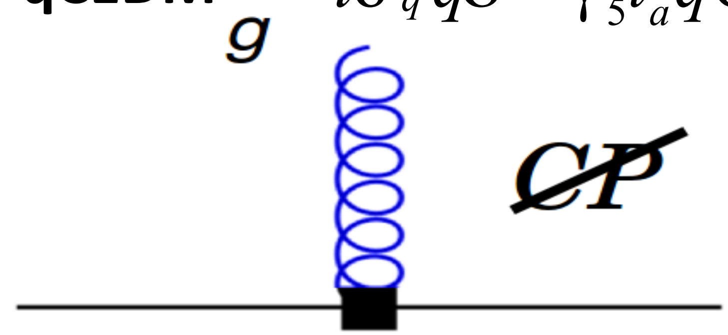
Heavy baryon EDM, a probe for new physics

- EDM of fundamental particles from the structure of quarks and gluons, and processes with photon and flavour-diagonal coupling
- A measurement of a heavy baryon EDM is **directly sensitive** to:

qEDM $-\frac{i}{2}\delta_q \bar{q}\sigma^{\mu\nu}\gamma_5 q F_{\mu\nu}$



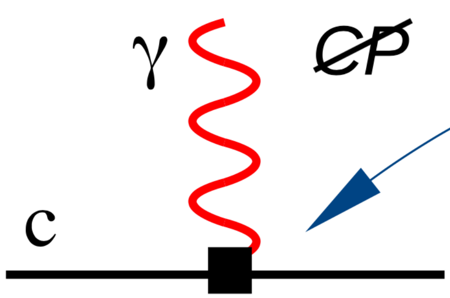
qCEDM $i\tilde{\delta}_q \bar{q}\sigma^{\mu\nu}\gamma_5 t_a q G^a_{\mu\nu}$



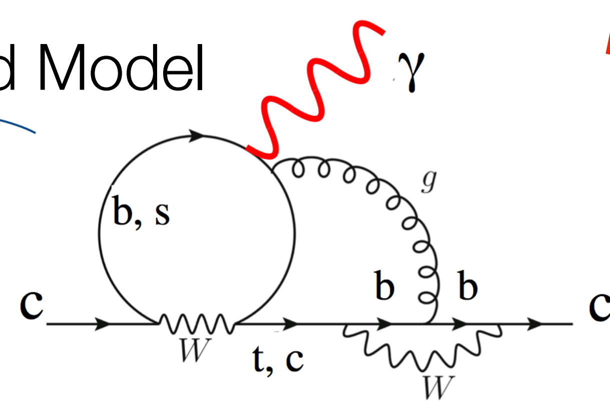
Charm EDM in Standard Model ~10^{-32} e cm

Charm EDM with new physics ~$5 \cdot 10^{-17}$ e cm

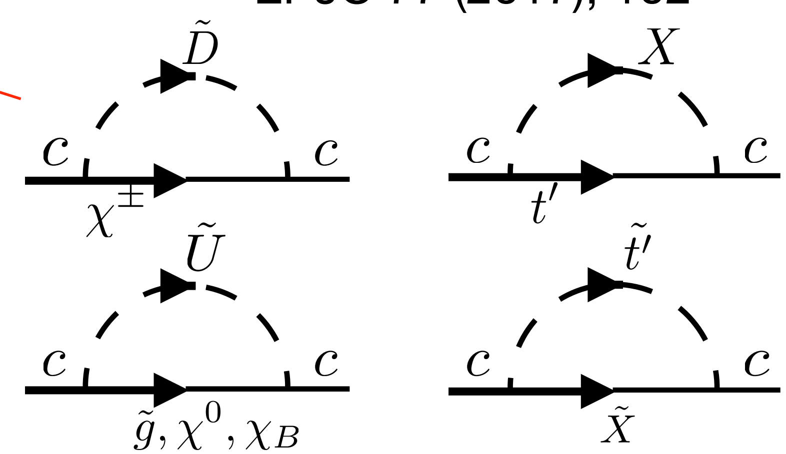
EPJC 77 (2017), 102



Standard Model



New physics



- EDM observation = clear signature of **new physics**

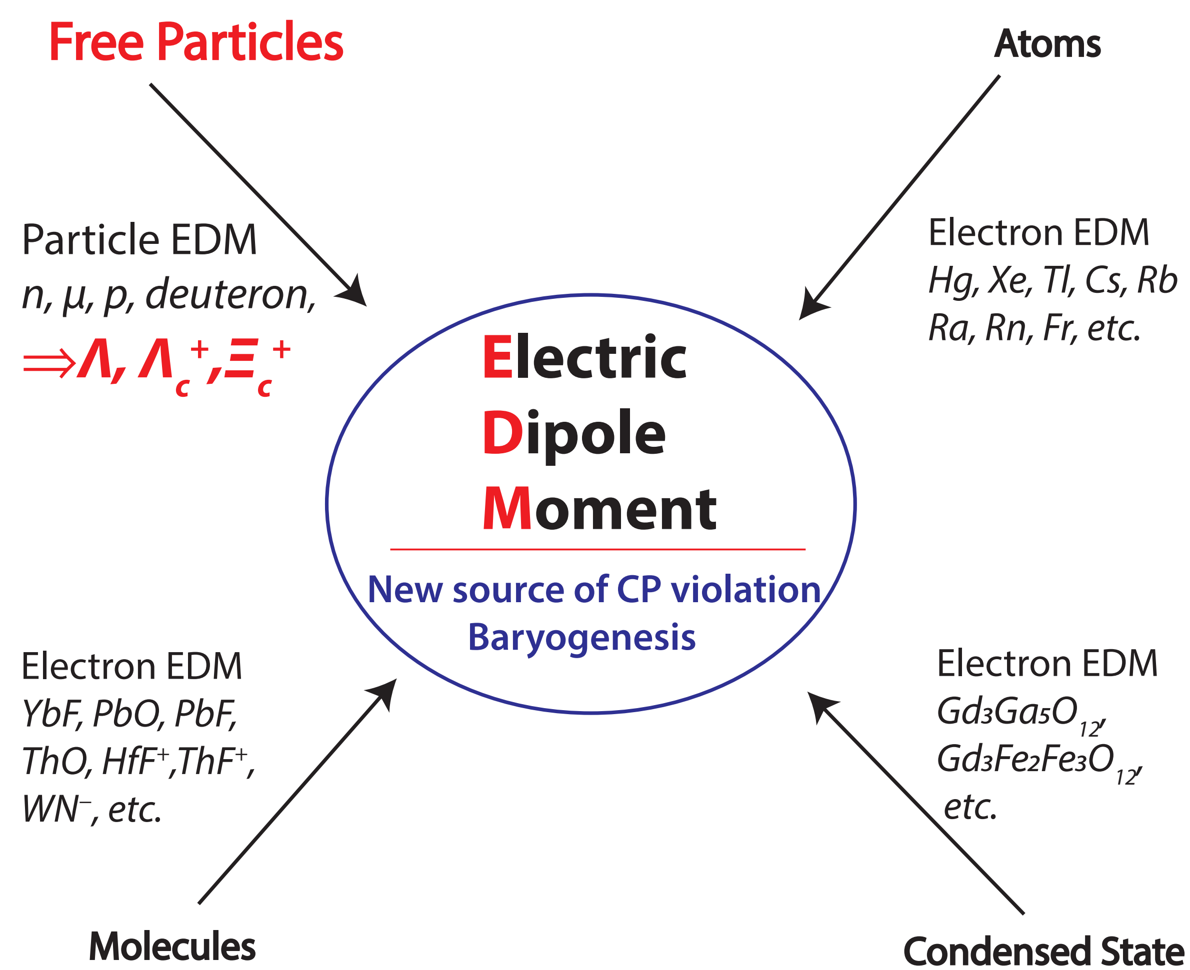
Current limits on EDM

- Intense EDM program is ongoing worldwide and new experiments are planned

- Possibility to contribute at LHCb searching for Λ strange and (first time) Λ_c^+, Ξ_c^+ charm baryon EDM

Particle	Limit/Measurement [e cm]	SM limit [factor to go]
e	$<1.05 \times 10^{-27}$	10^{11}
μ	$<1.8 \times 10^{-19}$	10^{8}
τ	$(-2.2 < d_\tau < 4.5) \times 10^{-17}$	10^{7}
n	$<2.9 \times 10^{-26}$	10^{4}
p	$<0.54 \times 10^{-23}$	10^{6}
Λ^0	$(-3.0 \pm 7.4) \times 10^{-17}$	10^{11}
$\nu_{e,\mu}$	$<2 \times 10^{-21}$	
ν_τ	$<5.2 \times 10^{-17}$	
Hg-atom	$<3.1 \times 10^{-29}$	$\leq 10^{4}$

Ann. Phys. (Berlin) 525, No. 8–9 (2013)



Charm and strange baryon MDM

- Experimental anchor points for test of low-energy QCD models, related to non-perturbative QCD dynamics
  - discriminate among proposed models, which predict significantly different strange/charm MDM values
- Test of quark substructure: an anomalous MDM would be a sign for strange/charm quark substructure
- Measurement of MDM of particle and antiparticle would allow a test of *CPT* symmetry

I.J. Kim, Nucl. Phys B 229 (1983) 251-268

V.V. Baublis et al., NIMB 90 (1994) 112-118

Experimental method

EDM proposal

Fill the experimental gap in **charm and strange baryon electric and magnetic dipole moment** measurements

EPJC (2017) 77:181

EDM proposal

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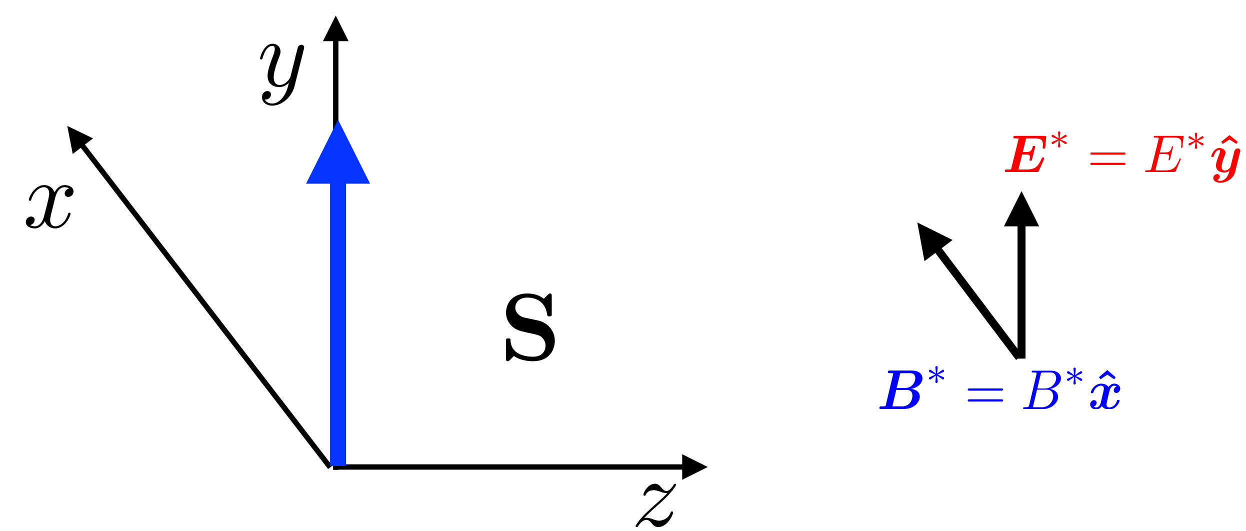
EPJC (2017) 77:181

EDM $\boldsymbol{\delta} = d\mu_N \frac{\mathbf{S}}{2}$ and magnetic dipole moment MDM $\boldsymbol{\mu} = g\mu_N \frac{\mathbf{S}}{2}$

Spin precession in external electromagnetic field (**E***⊥**B*** in particle rest frame)

$$\frac{d\mathbf{S}}{dt} = \boldsymbol{\mu} \times \mathbf{B}^*$$



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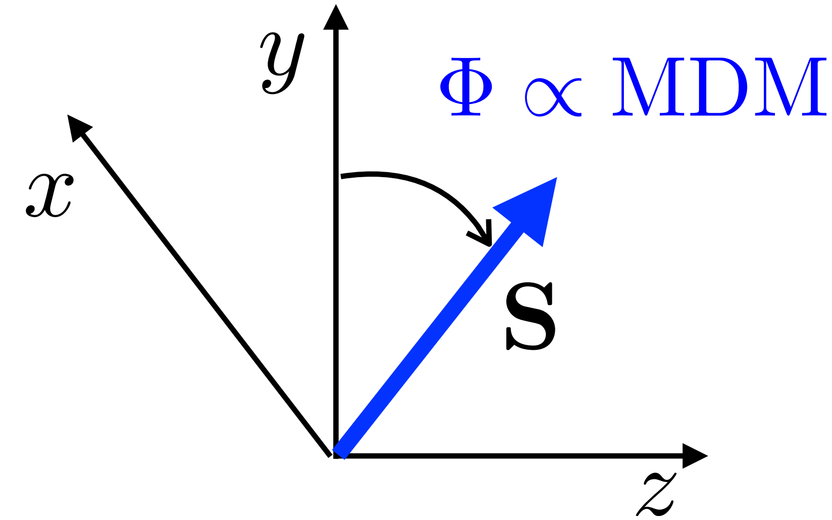

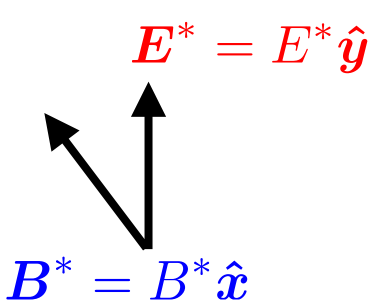

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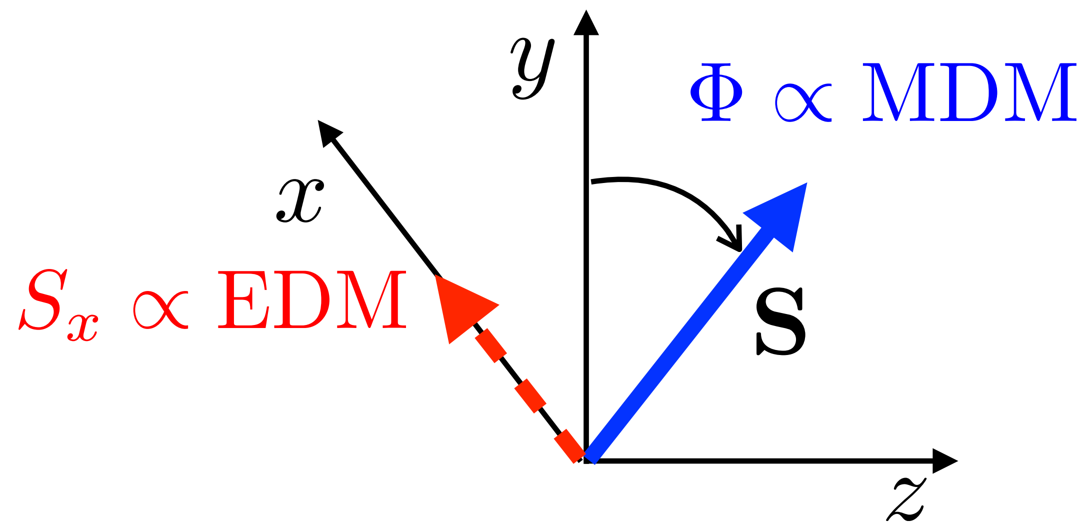
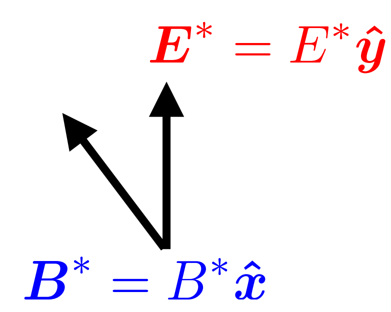
Spin precession in external electromagnetic field (**E*⊥B*** in particle rest frame)

$$\frac{d\mathbf{S}}{dt} = \boldsymbol{\mu} \times \mathbf{B}^* + \boldsymbol{\delta} \times \mathbf{E}^*$$





EDM proposal

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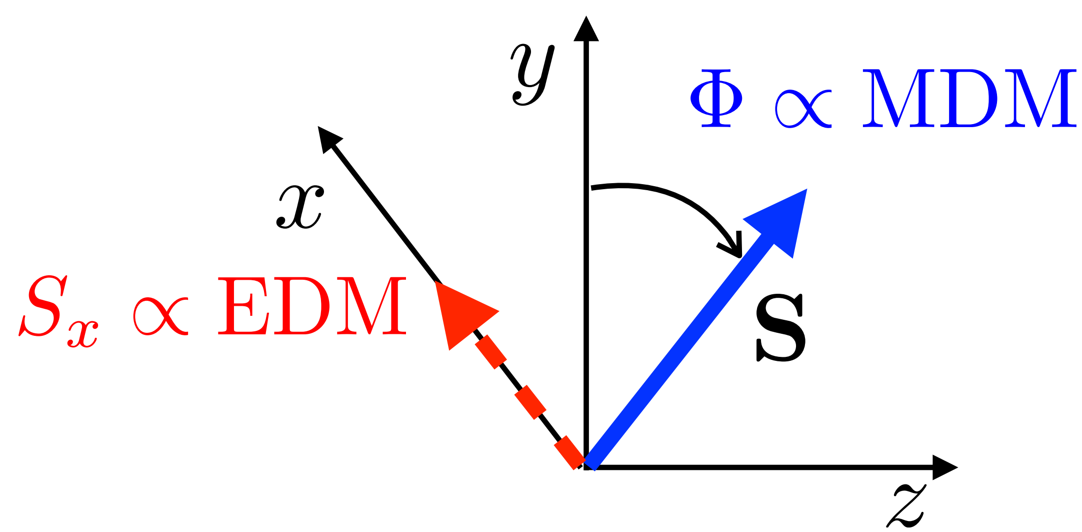
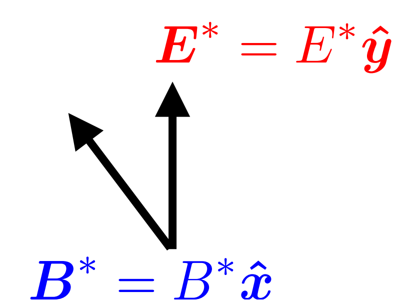
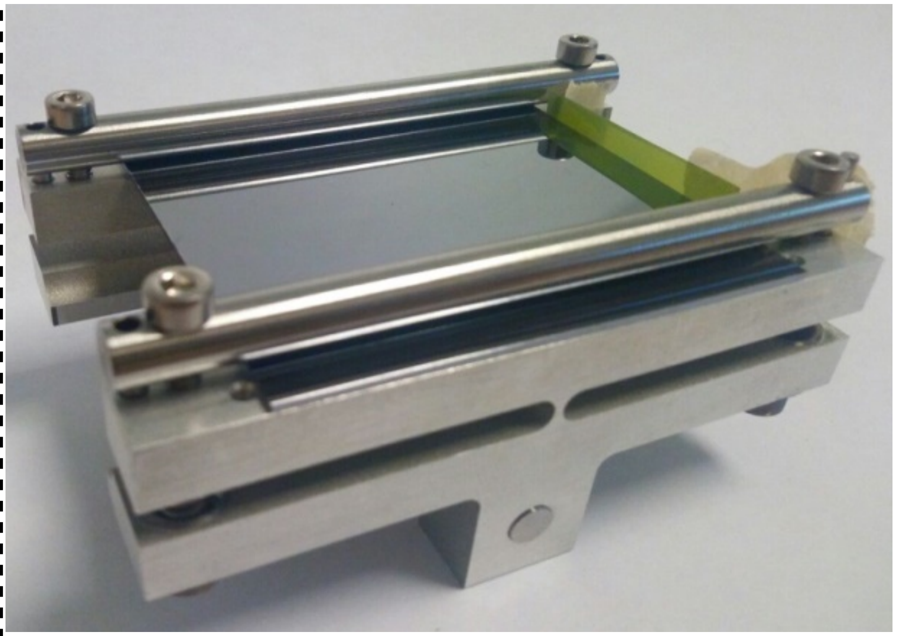


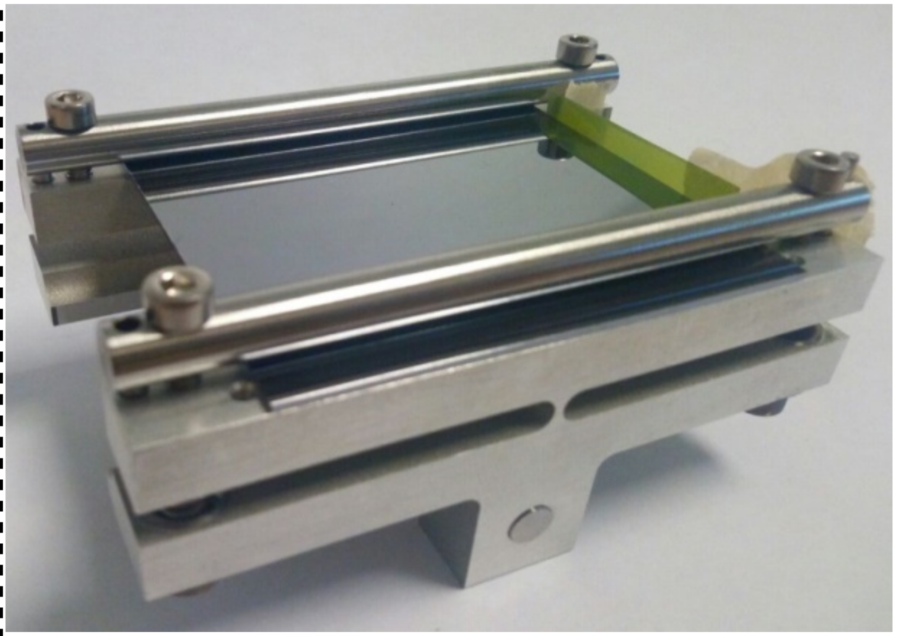


- Necessary sizeable spin precession: $\Phi \propto \frac{geB^*}{mc} t \sim \frac{\pi}{2}$
- "Ad hoc" solutions for charm and strange baryons

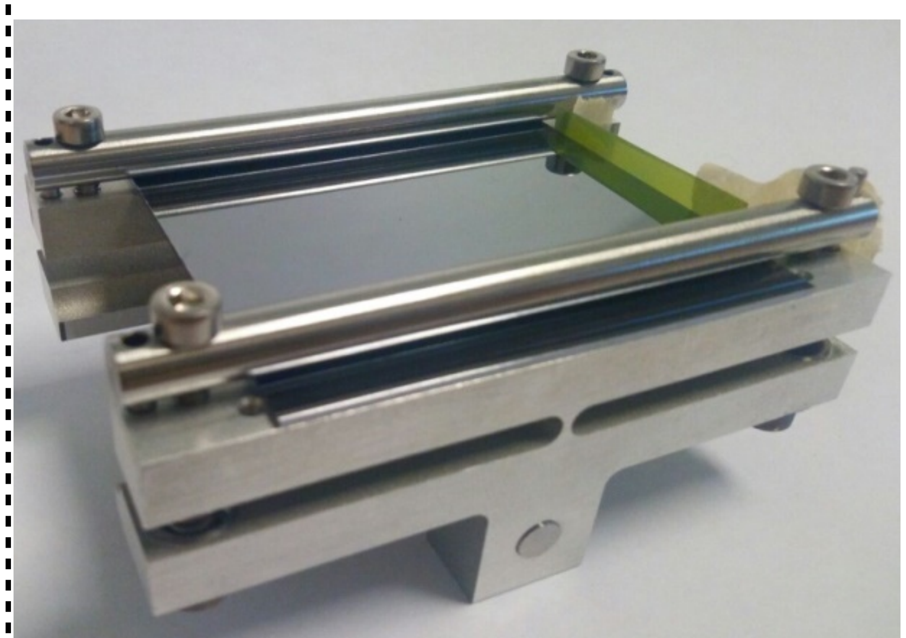
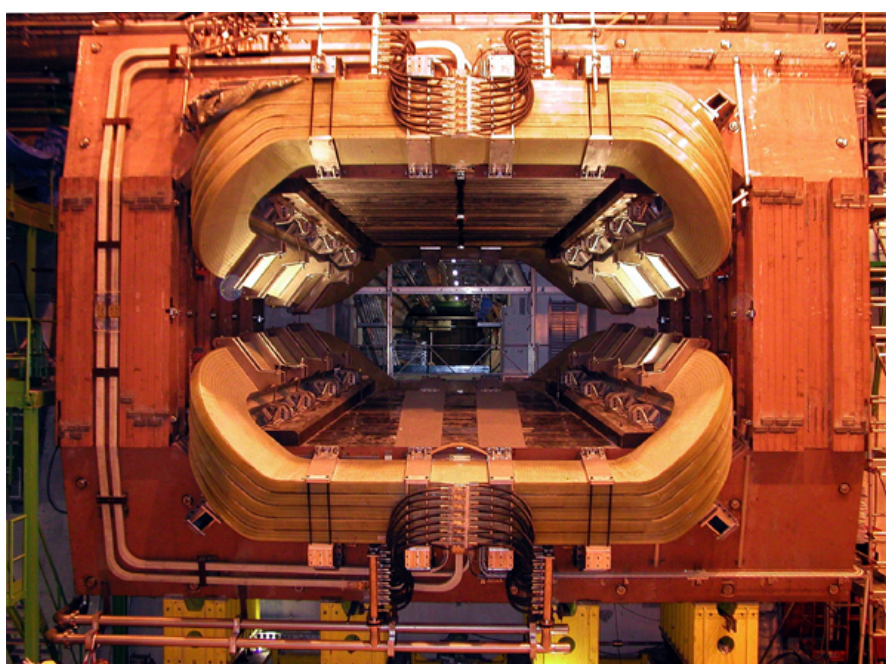
EDM proposal overview

Baryon	Solution	EDM	MDM
Charm Λ_c^+, Ξ_c^+ lifetime $\sim 10^{-13}$ s		First search sensitivity **$\sim 10^{-17}$ *e* cm**	First measurement for **QCD** & baryon internal structure test **$<10^{-3}$ precision**

EDM proposal overview

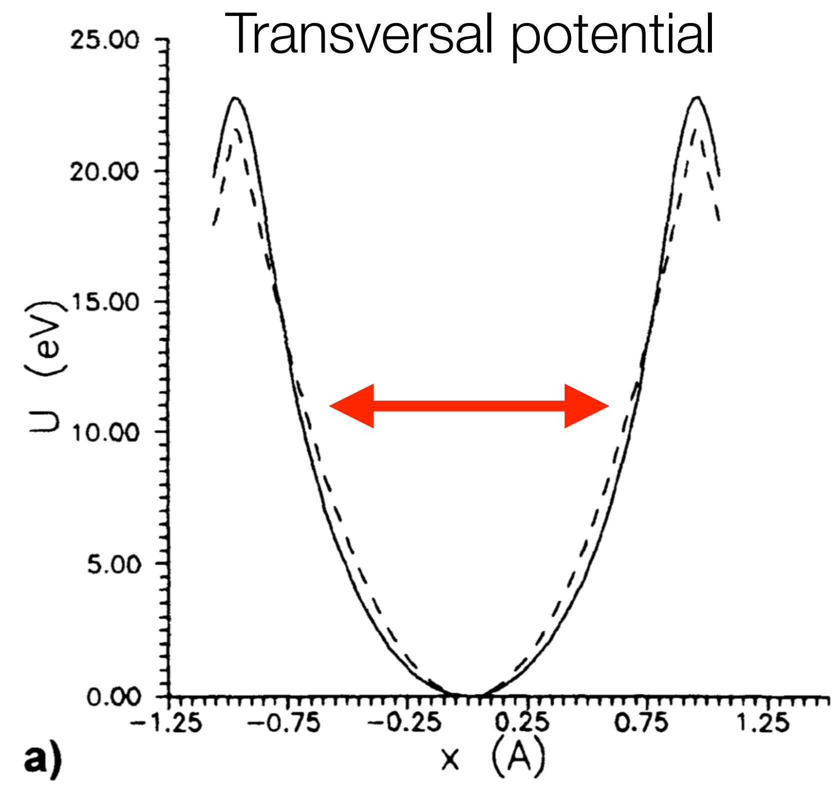
Baryon	Solution	EDM	MDM
Charm Λ_c^+, Ξ_c^+ lifetime $\sim 10^{-13}$ s		First search sensitivity $\sim$**10^{-17} e cm**	First measurement for **QCD** & baryon internal structure test **<10^{-3} precision**
Strange Λ lifetime $\sim 10^{-10}$ s	Highly boosted and polarised Λ (anti-Λ) from weak charm baryon decays **LHCb** forward detector and **dipole magnet** B~1 T	Push EDM sensitivity of factor 100 **$\sim 10^{-18}$ e cm**	First test of **CPT** via strange baryon, anti-baryon MDM **<10^{-3} precision**

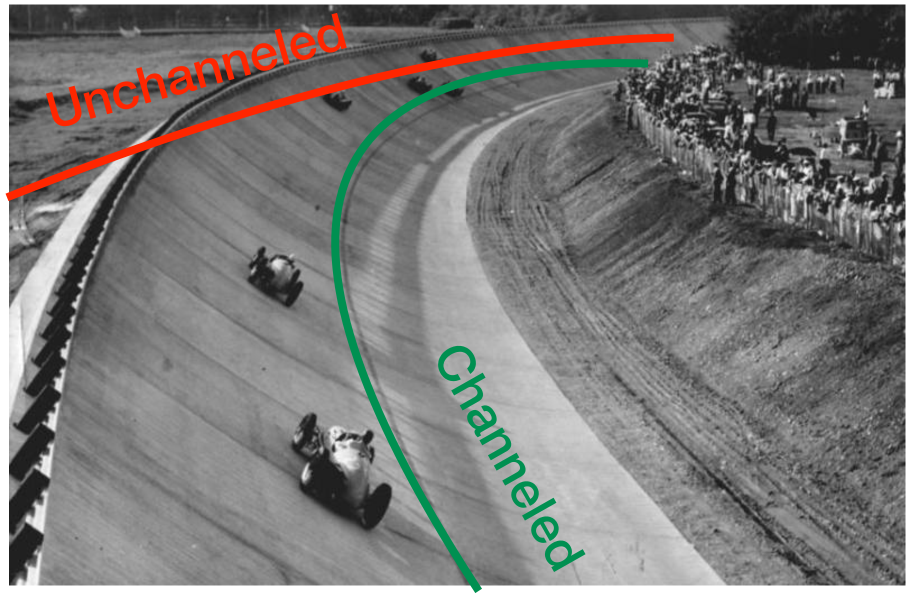
EDM proposal overview

Baryon	Solution	EDM	MDM
Charm Λ_c^+, Ξ_c^+ lifetime ~10^{-13} s		First search sensitivity **~10^{-17} *e* cm**	First measurement for **QCD** & baryon internal structure test **<10^{-3} precision**
Strange Λ lifetime ~10^{-10} s		Push EDM sensitivity of factor 100 **~10^{-18} *e* cm**	First test of **CPT** via strange baryon, anti-baryon MDM **<10^{-3} precision**

Channeling in bent crystals

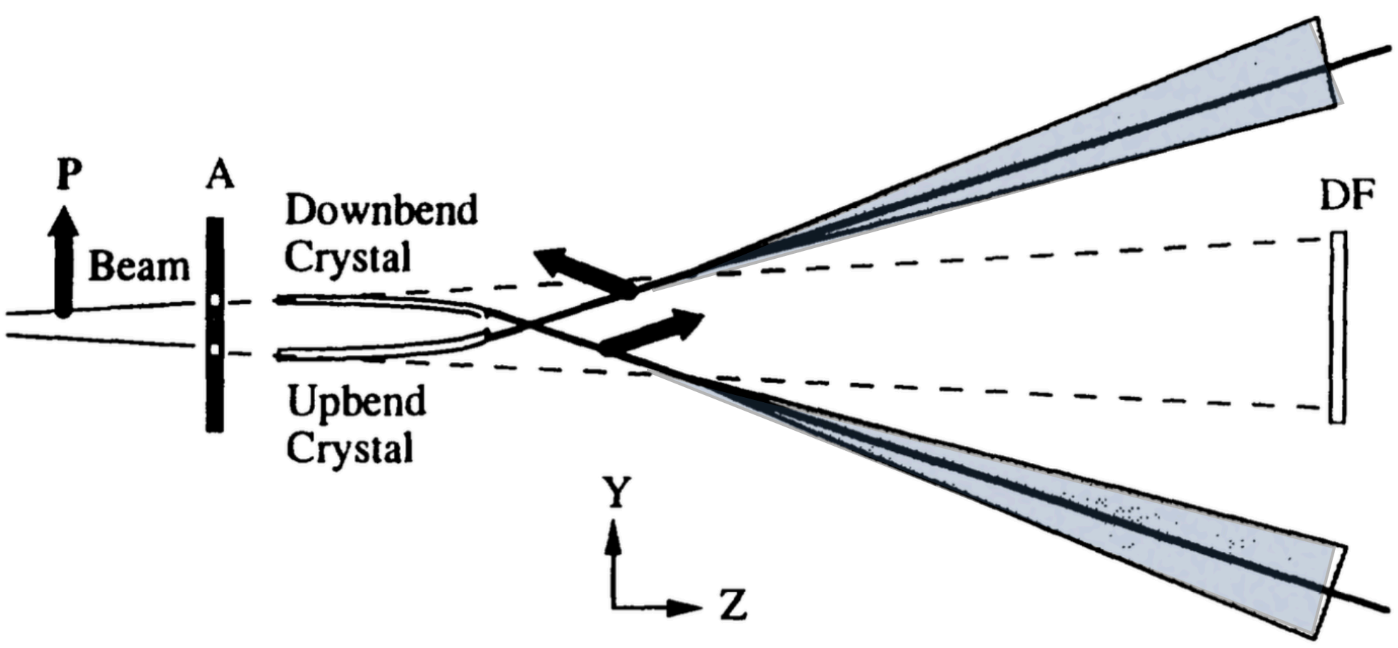
- Potential well between crystal planes
- Incident positive charge particle can be trapped if parallel to crystal plane (within few μrad)
- Well understood phenomenon (Lindhard 1965).
- Bent crystals can be used to:
  - steer high-energy particle beams
  - induce spin precession. Net **E** field in presence of centripetal force





Proof of principle in E761

- E761 Fermilab experiment firstly observed spin precession in bent crystals and measured MDM of Σ^+
  Phys. Rev. Lett. 69 (1992) 3286
- 350 GeV/c Σ^+ produced from interaction of 800 GeV/c proton beam on Cu target
- Used upbend and downbend silicon crystals L=4.5cm, θ_C=1.6 mrad to induce opposite spin precession



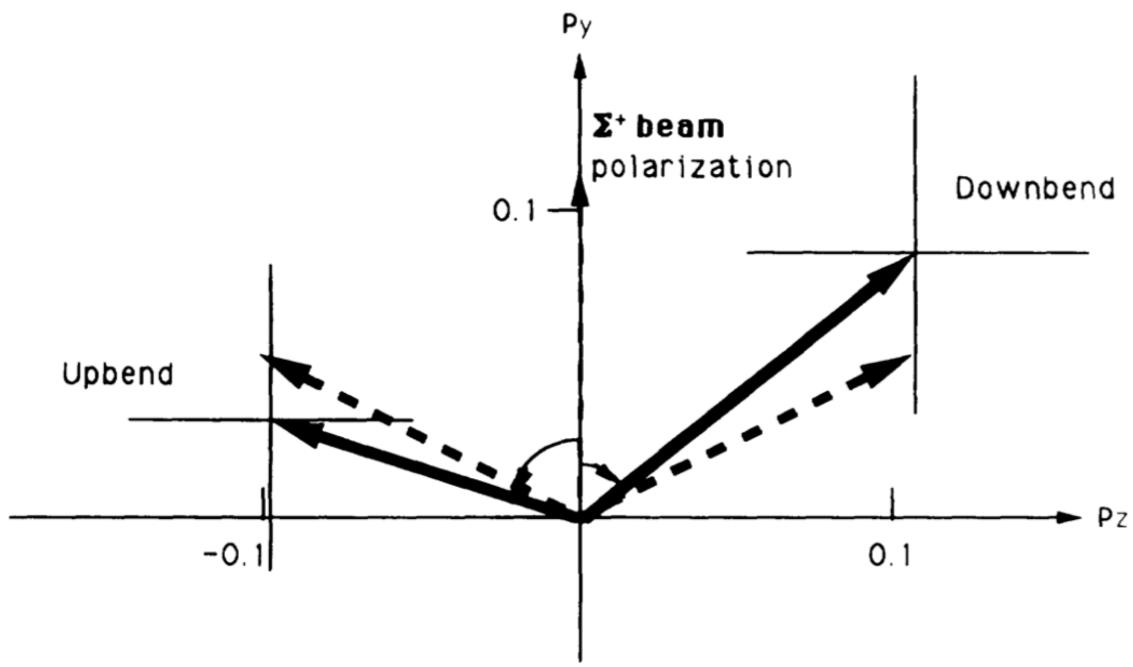
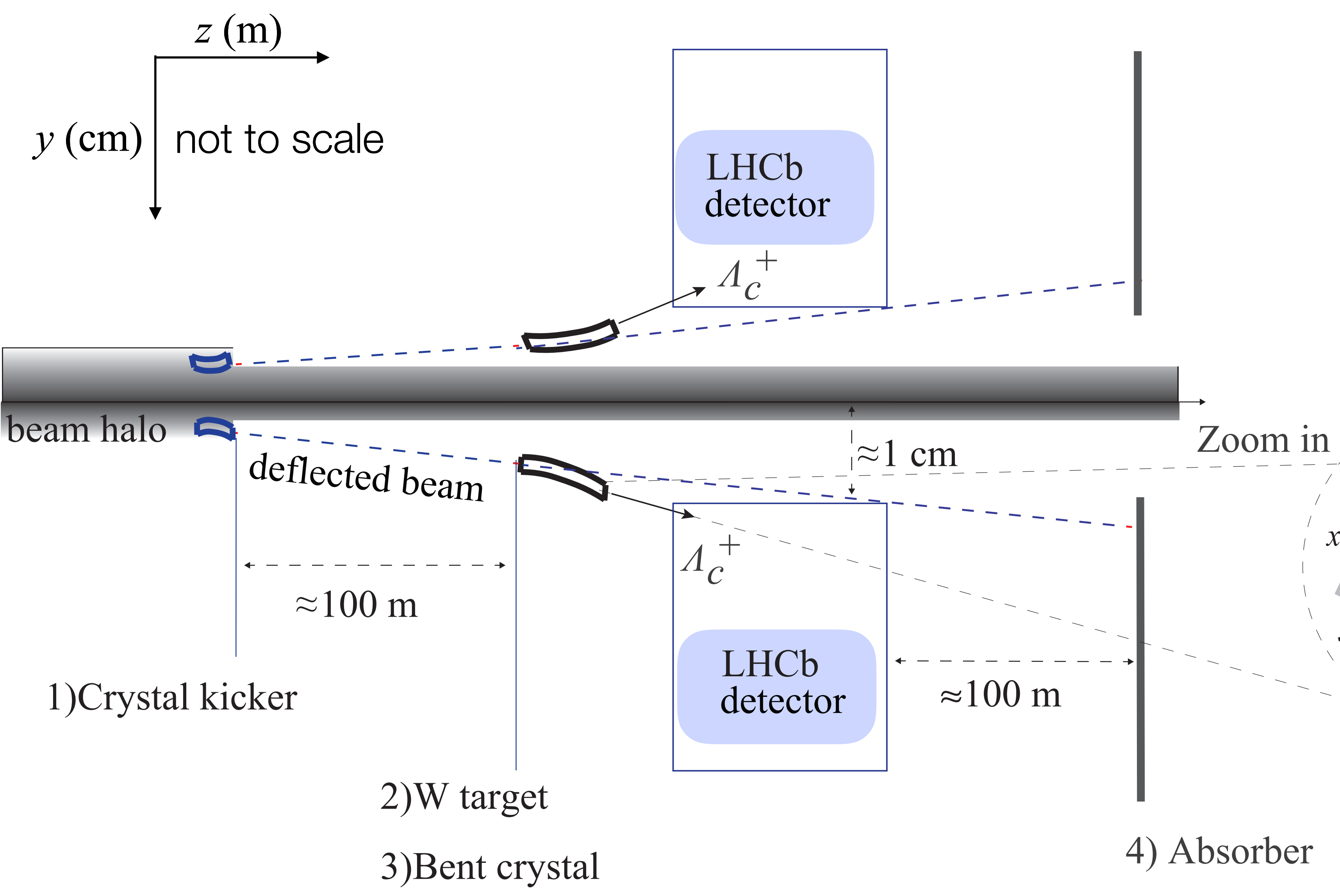
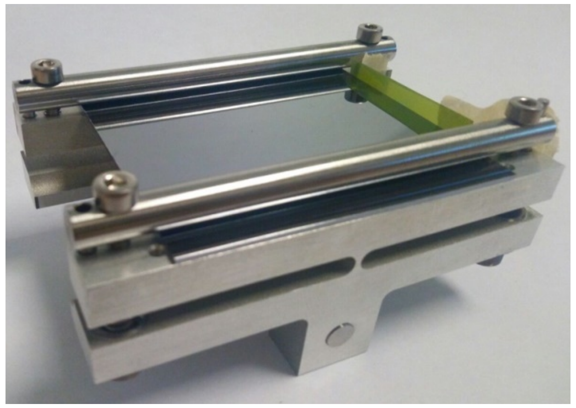


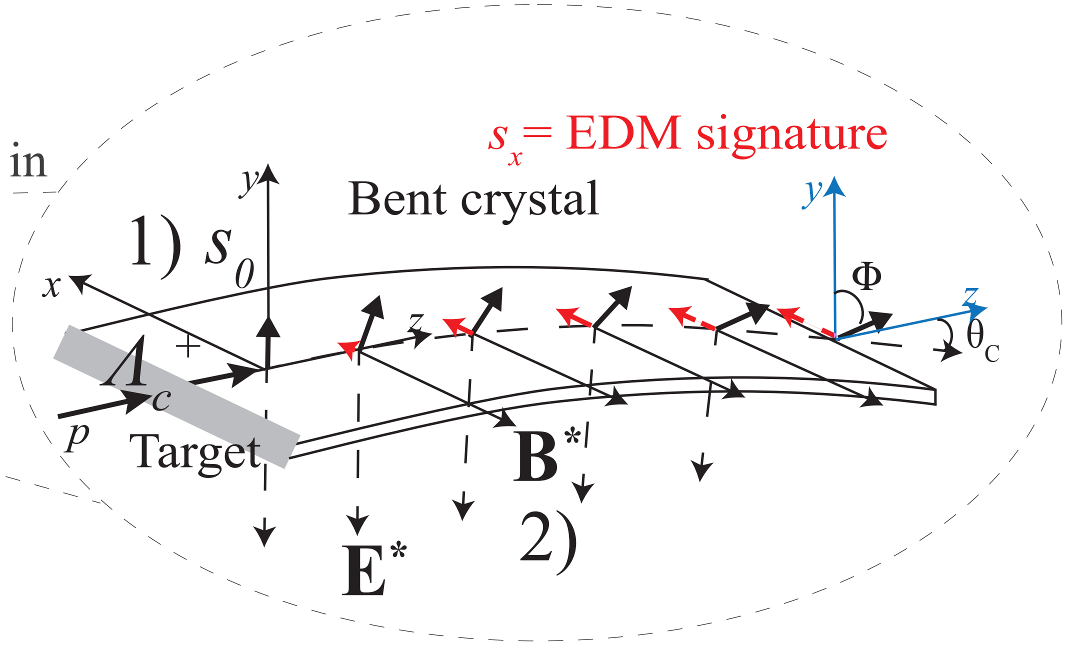
FIG. 3. Measured polarizations and uncertainties (1σ statistical errors) after spins have been processed by the two crystals. The dashed arrows show the expected precessions.

Novel fixed-target experiment at LHC for charm baryons

- $\color{red}{\text{EDM}}$/$\color{blue}{\text{MDM}}$ from spin precession of channeled baryons in **bent crystals**



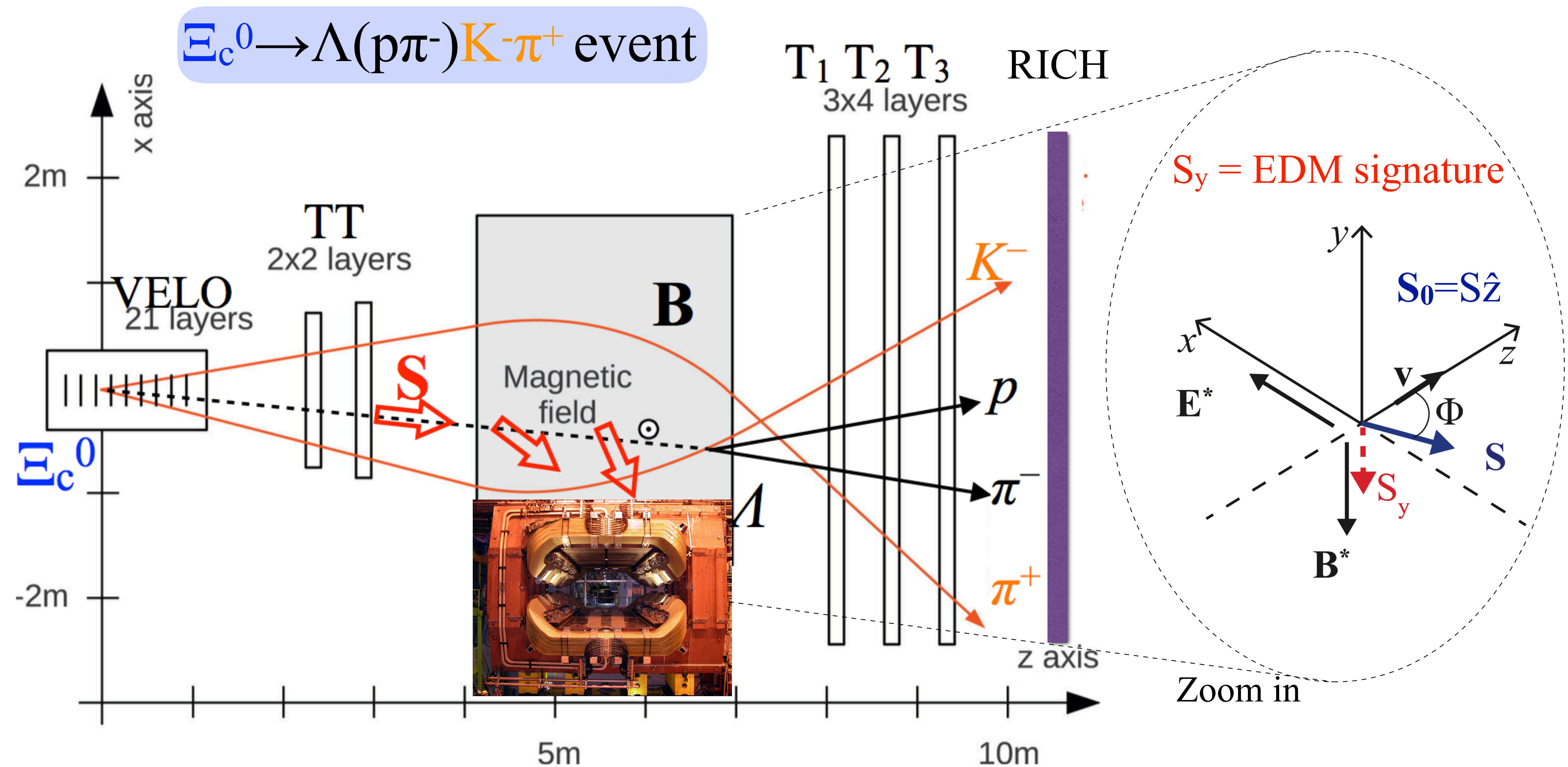




p extraction Λ_c^+ polarised production channeling spin precession event reconstruction

Novel experimental technique for strange baryons

- EDM/MDM from spin precession of Λ baryon in LHCb **dipole magnet**

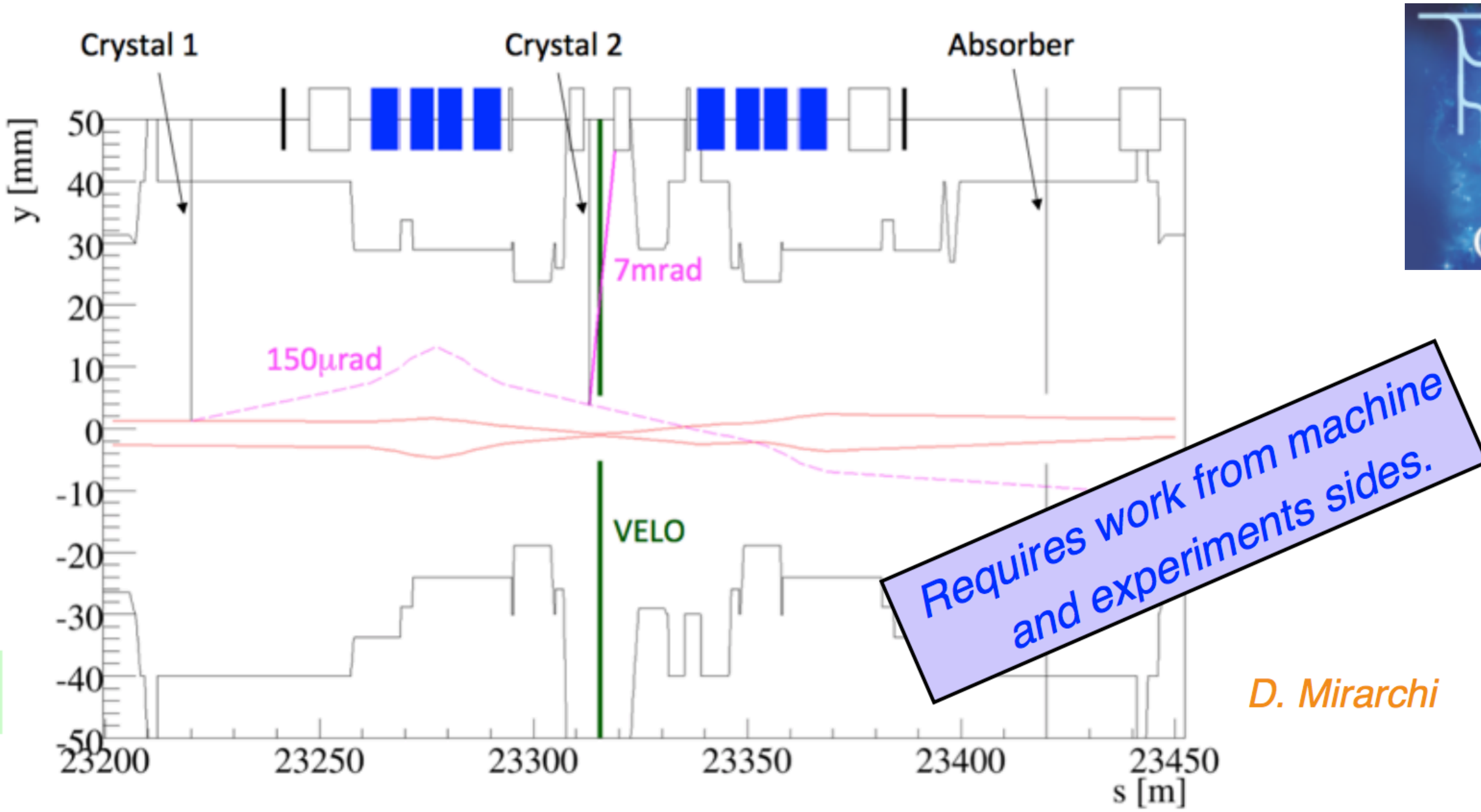


Λ polarised production   spin precession   event reconstruction

Simulation studies

Possible implementation at IP8

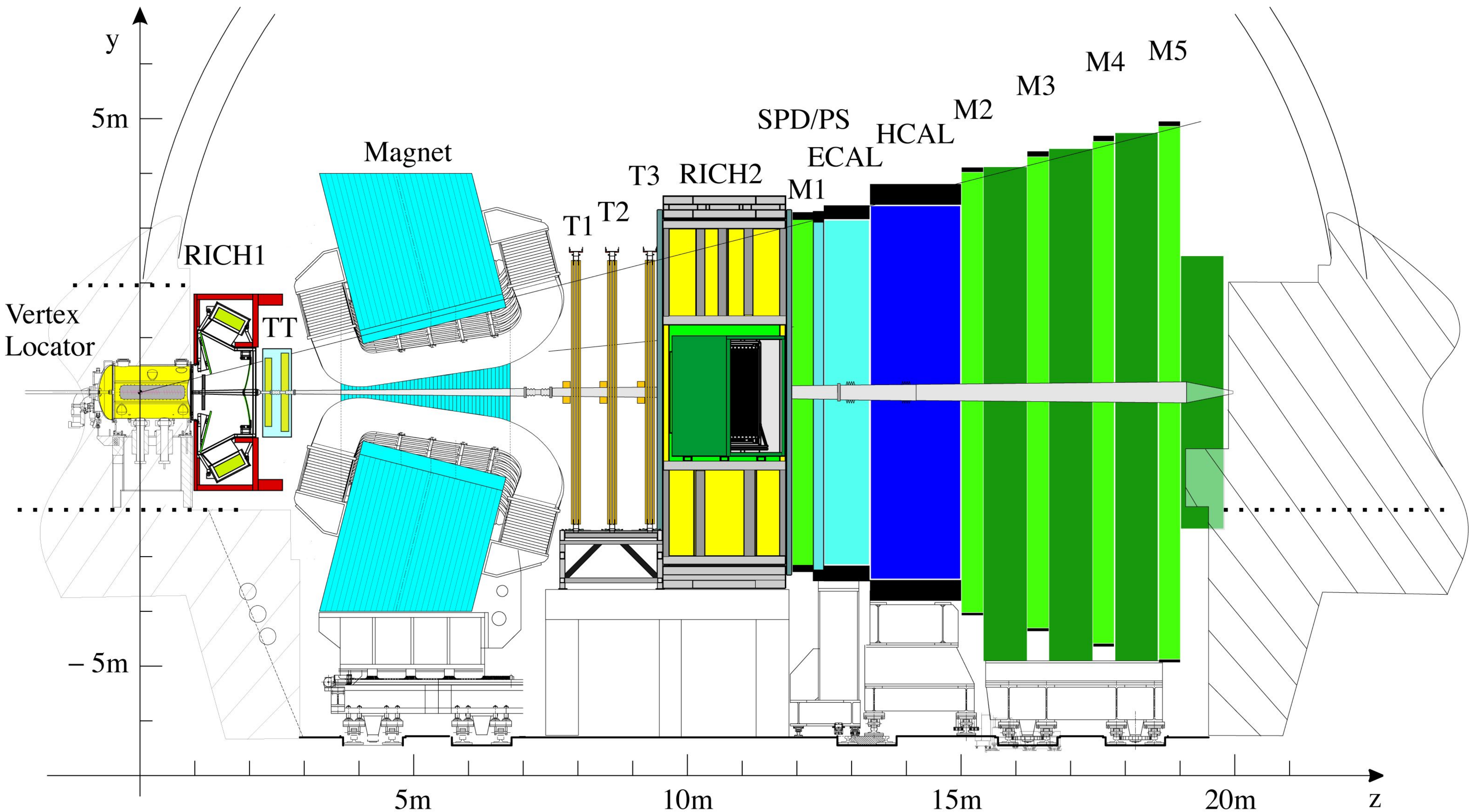
S. Redaelli, Physics Beyond Colliders, 01/03/2017



D. Mirarchi

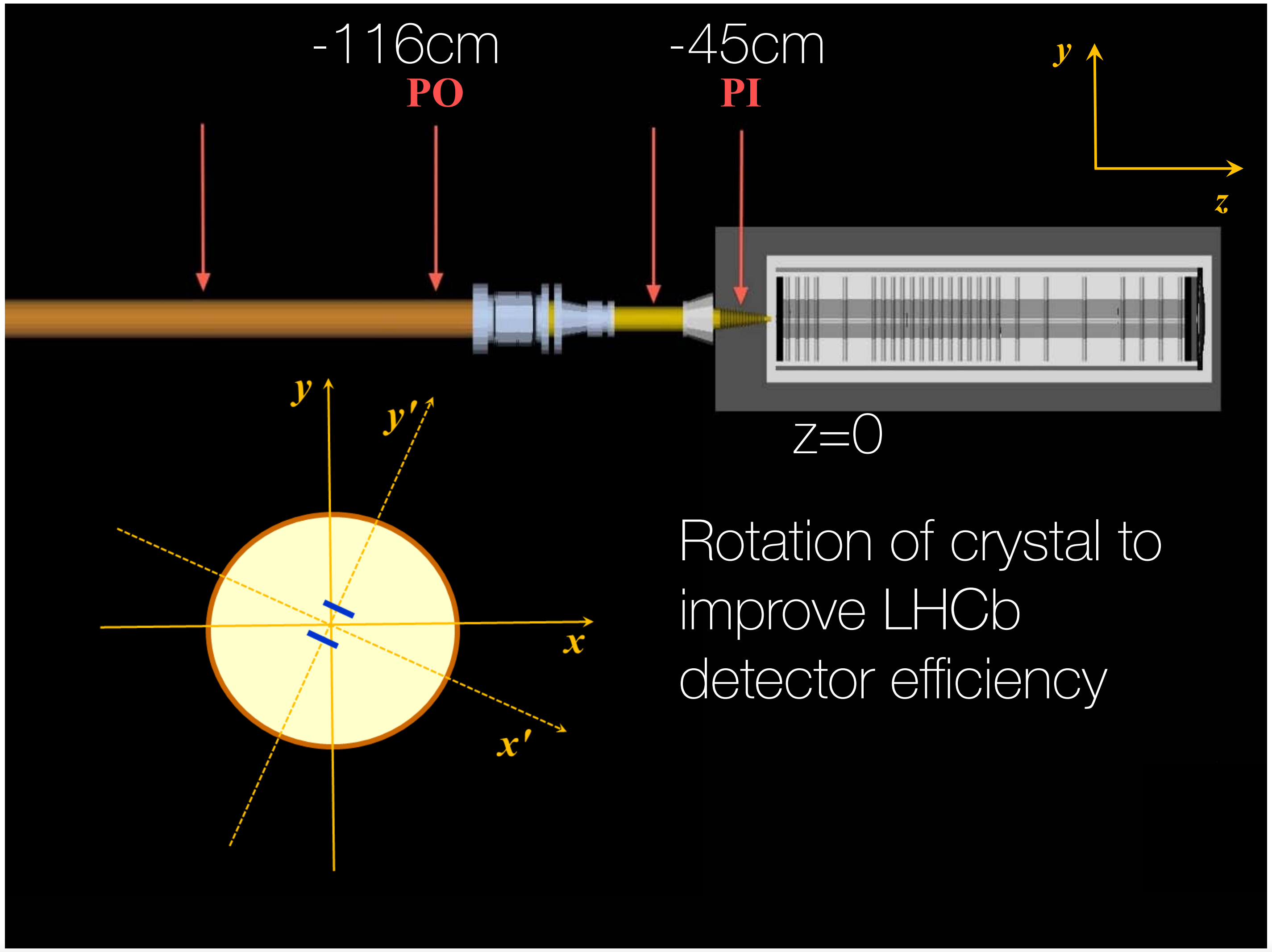
- Implementation in LHC seems feasible according to preliminary machine simulations. More studies are needed for optimal layout
- Feasibility studies of EDM, MDM measurements for realistic experimental conditions in LHCb in this talk

LHCb detector



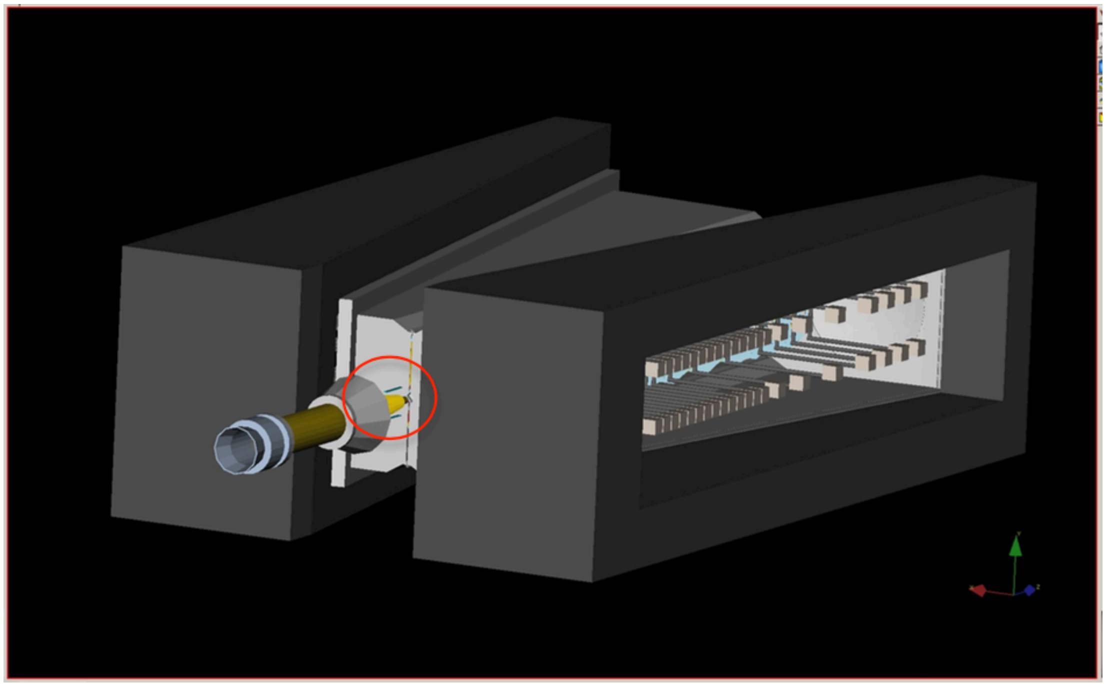
Fixed target & bent crystal

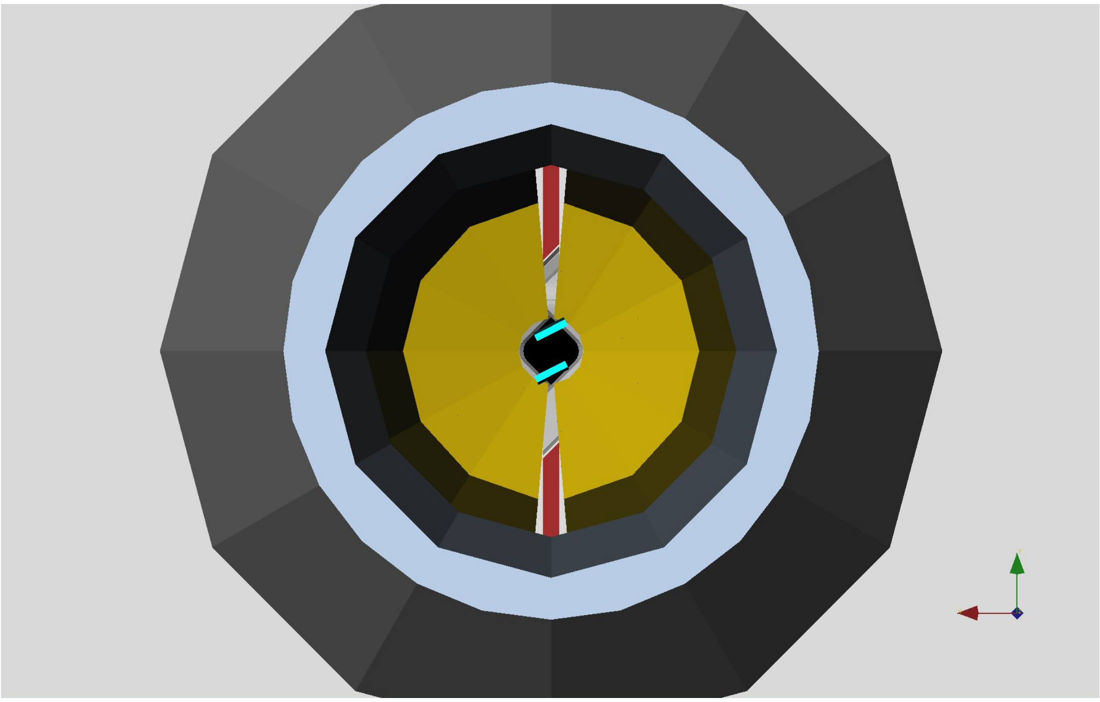
- Fixed target (W, d~0.5 cm) attached to a long bent crystal (Ge, L~5 cm, θ~15 mrad, Si, L~7 cm, θ~14 mrad)
- Bending angle θ>10 mrad determined by LHCb acceptance
- Close to VELO for optimal vertex resolution: e.g. distance from VELO sensors ~100 cm (PO)



Simulation studies

- Fixed target + bent crystal positioned in (0, 0.4, -116) cm

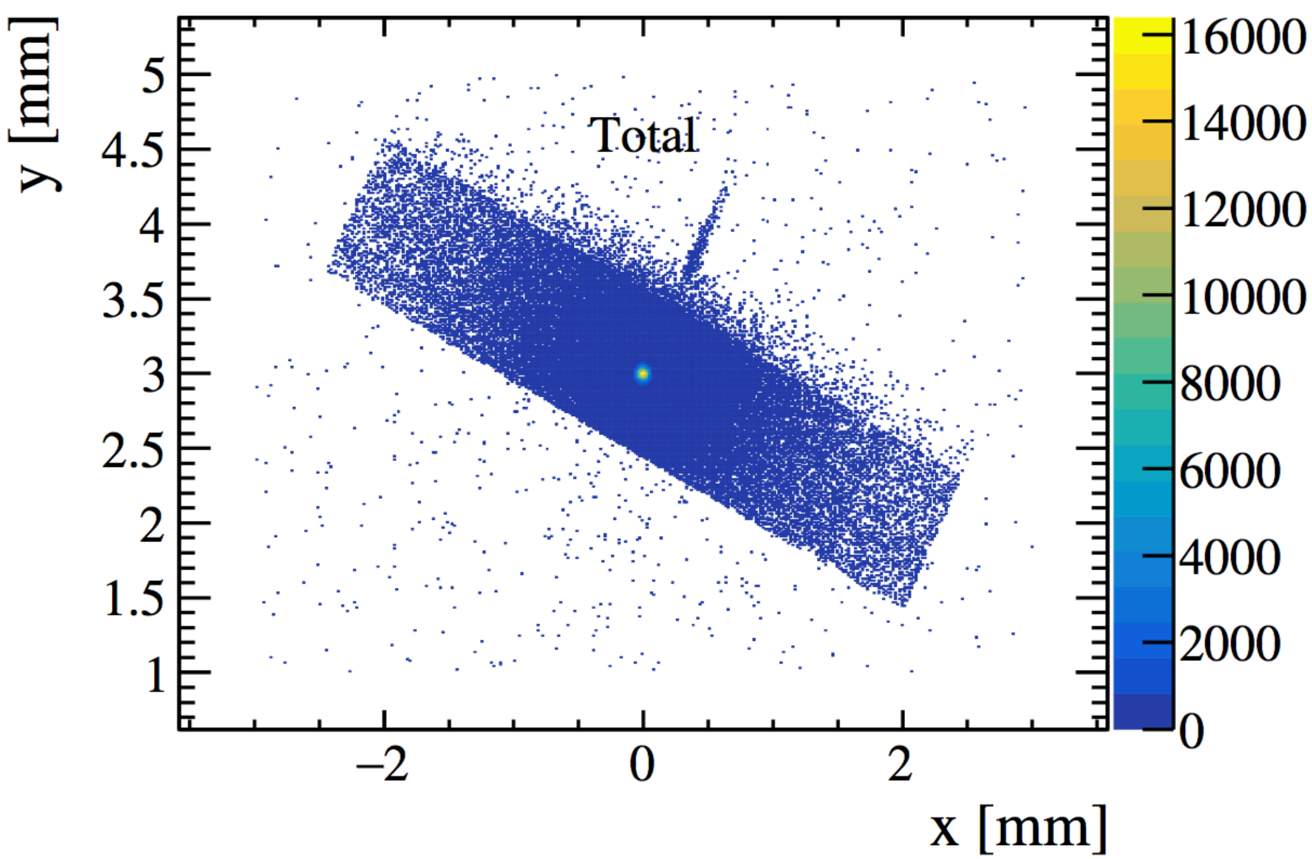


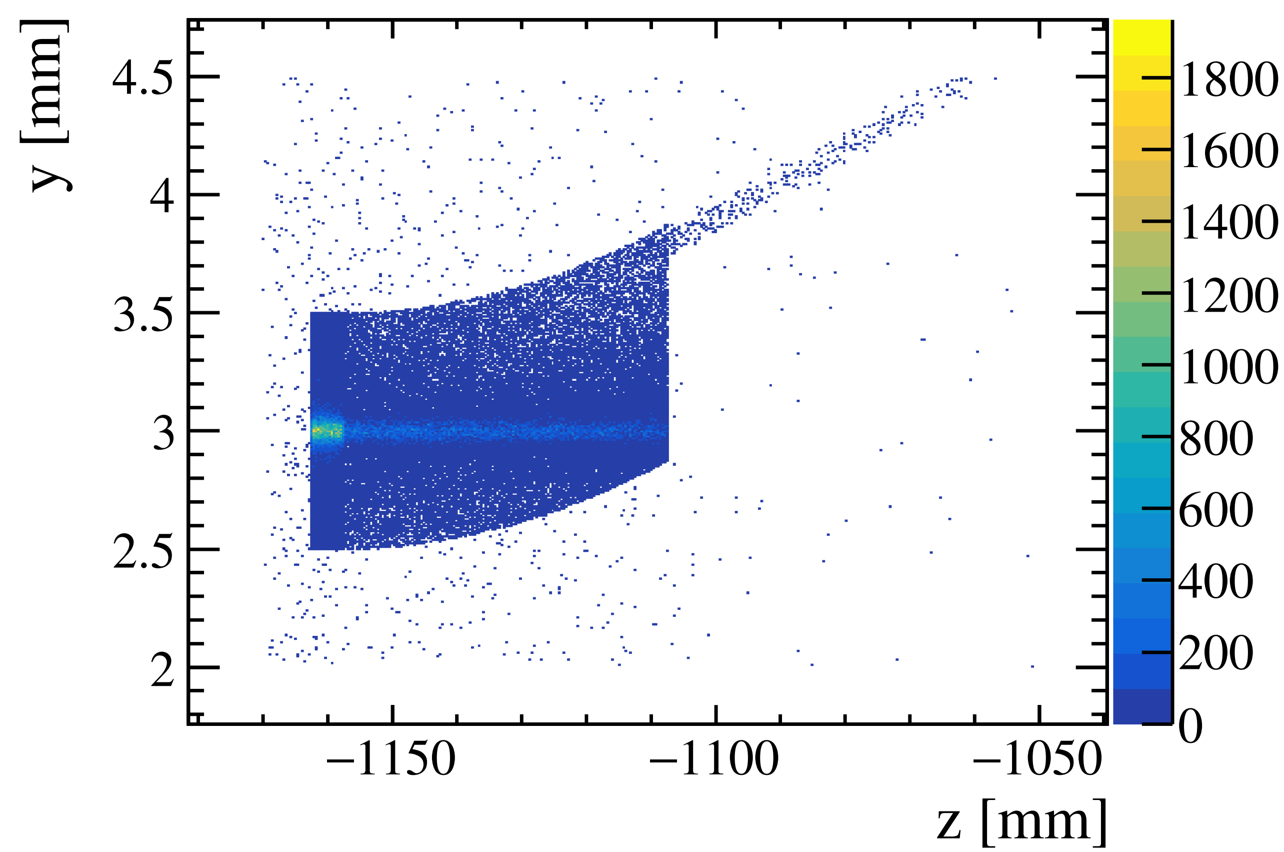


- Use EPOS for fixed-target minimum bias events, PYTHIA for baryons produced in pW hard collisions
- Use LHCb full simulation to reconstruct signal events and study the background

Fixed-target simulation

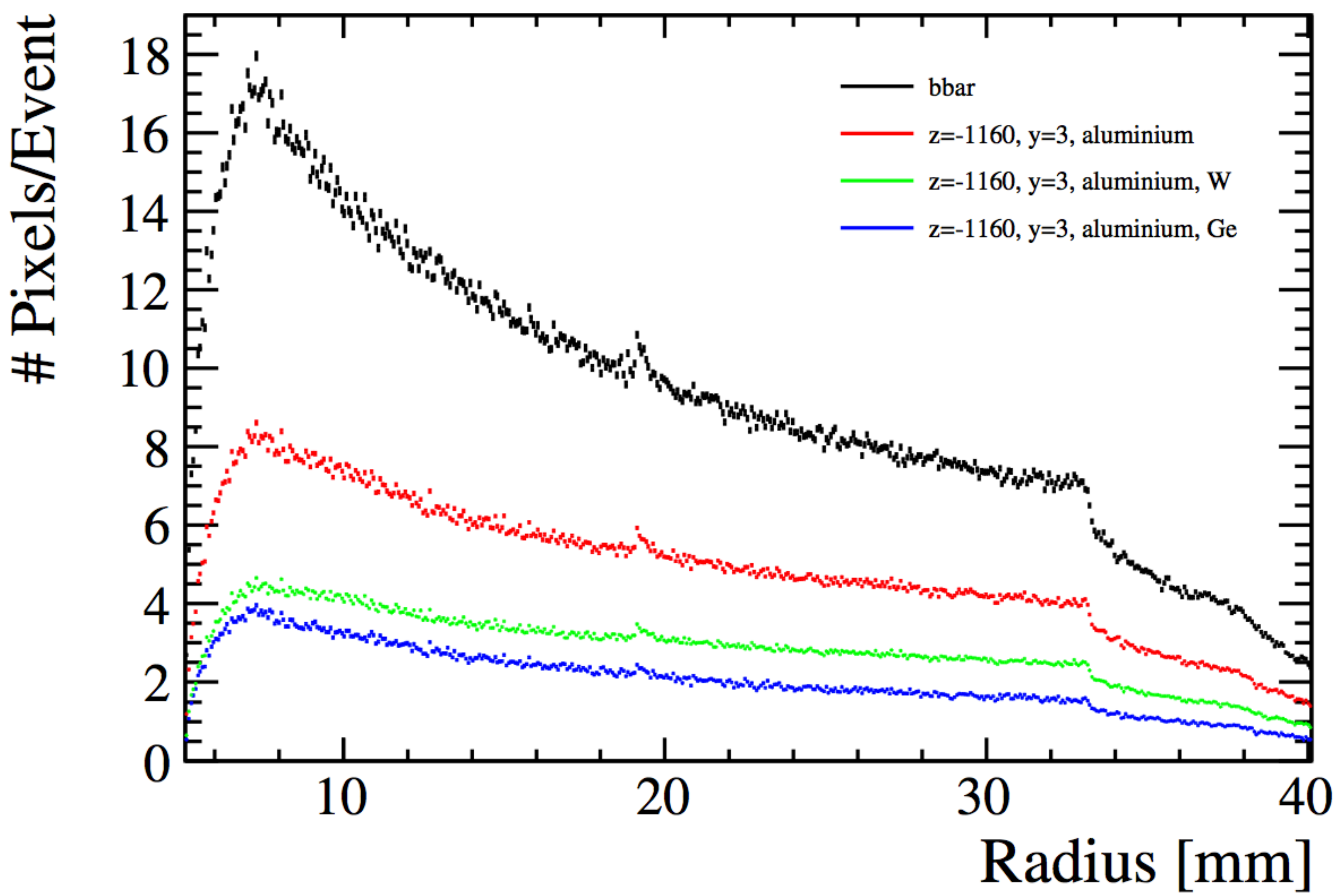
- Radiography of the target in (0, 0.3, -116) cm
- Distribution of origin vertex of stable charged particles in simulated events
- Simulated processes include: hadronic interactions, pair production, Bremsstrahlung, Compton, δ rays





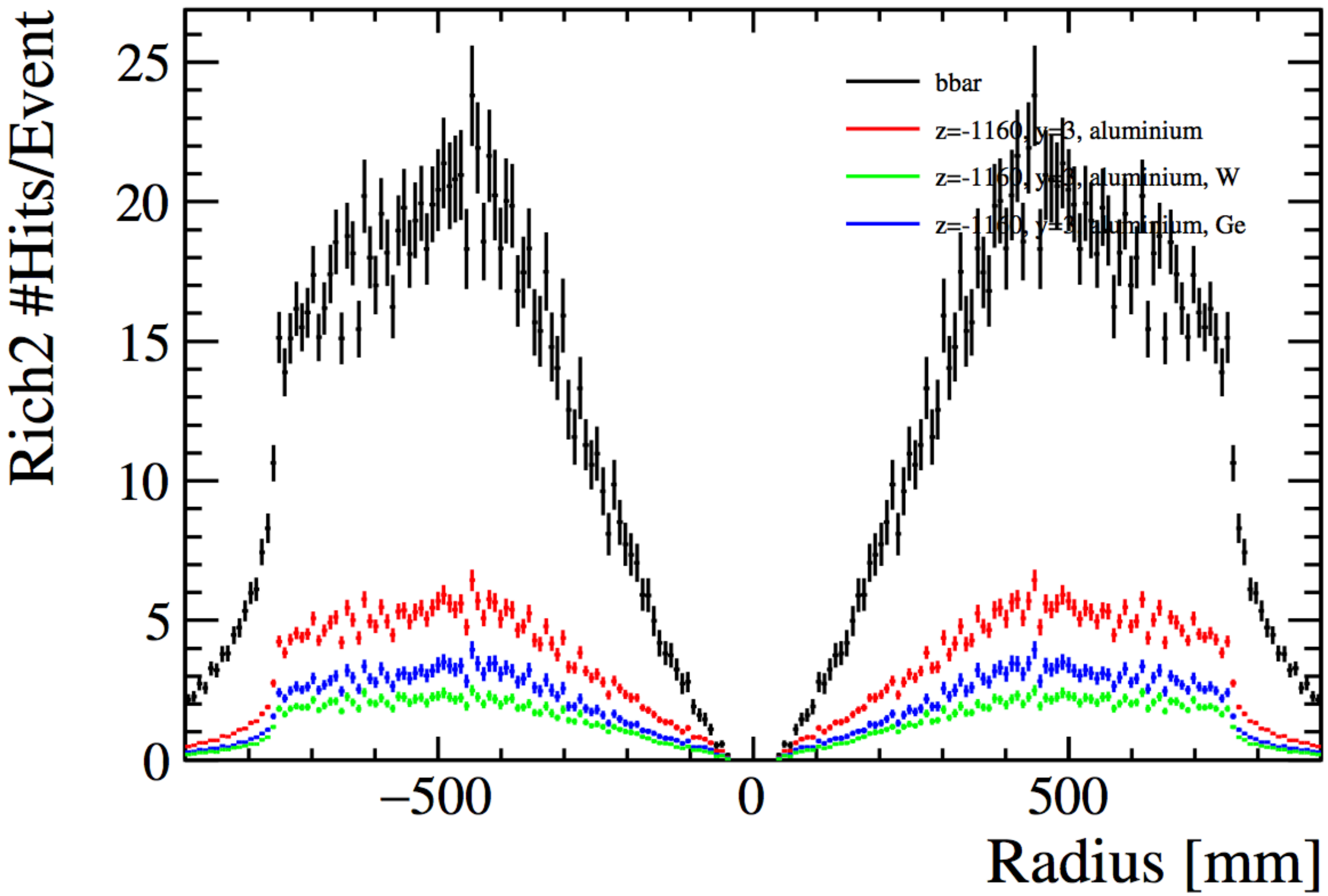
Clusters vs radial position in VELO

- Clusters in VELO 1st layer with 10^8 p/s on target (ν=0.81): ≲50% wrt generic bb events (ν=7.6)
- Crystal kicker regulates proton flux. Occupancy level is suitable for a dedicated run, also for higher proton flux



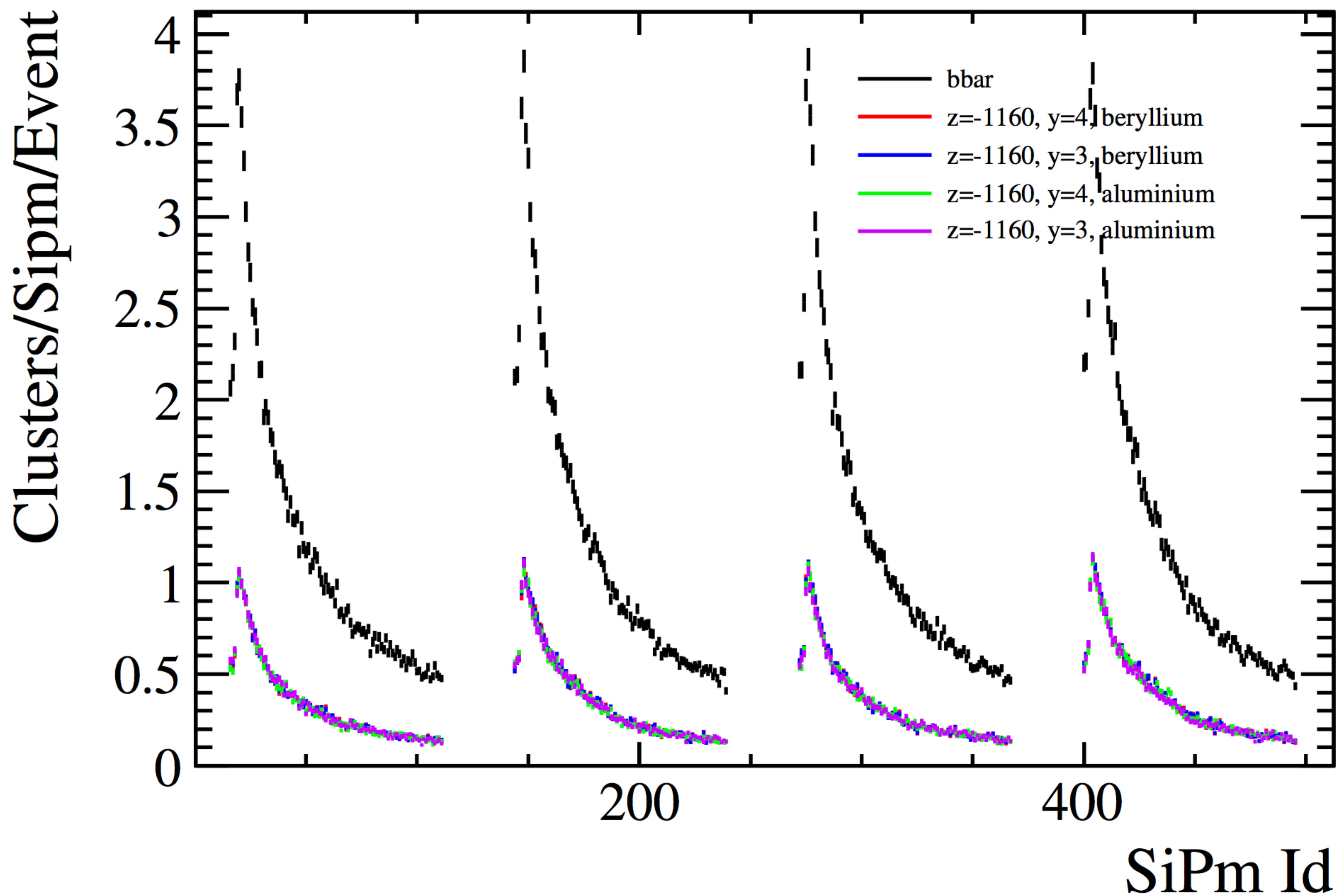
Hits in RICH

- Number of hits in Rich2 are also ≲30% wrt nominal collisions



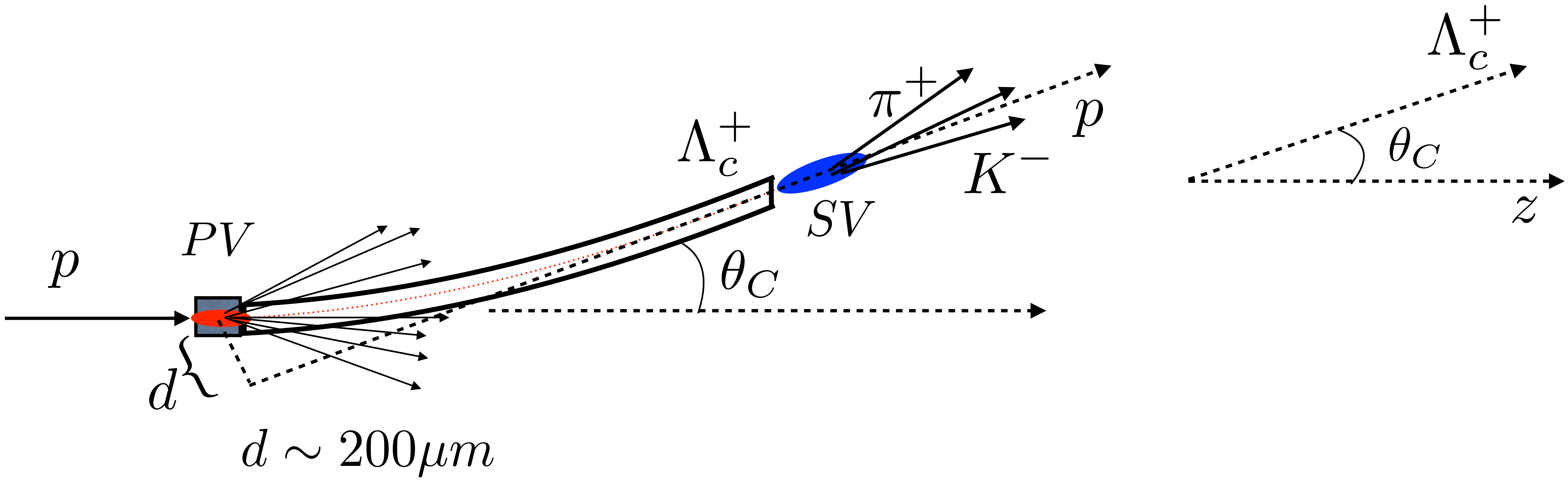
Clusters in SciFi

- Clusters vs SiPM number in SciFi L0
- Fixed-target: clusters ≲30% wrt bb collisions



Identification of signal events

- About 10^{-4}-10^{-3} Λ_c^+ produced in the target are channeled in the bent crystal

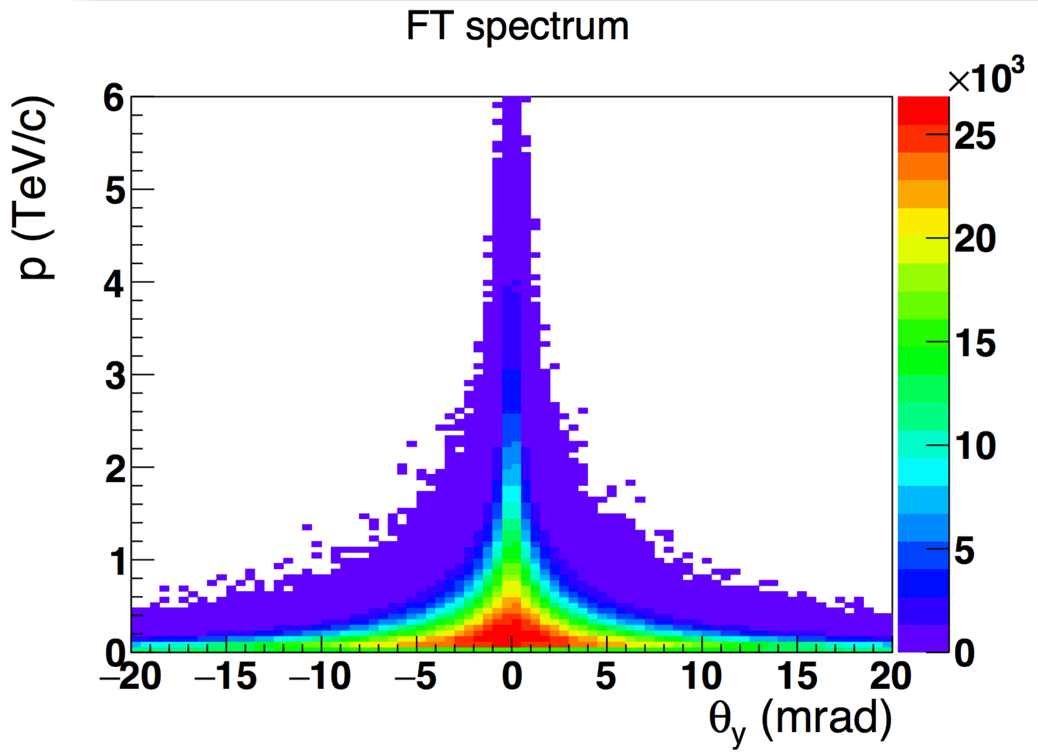


- Use PV to identify Λ_c^+ produced in W target, and Λ_c^+ vertex helps to identify decays outside of the crystal (max spin precession)

- Λ_c^+ angle determined by crystal bending angle, e.g. θ_C=15 mrad

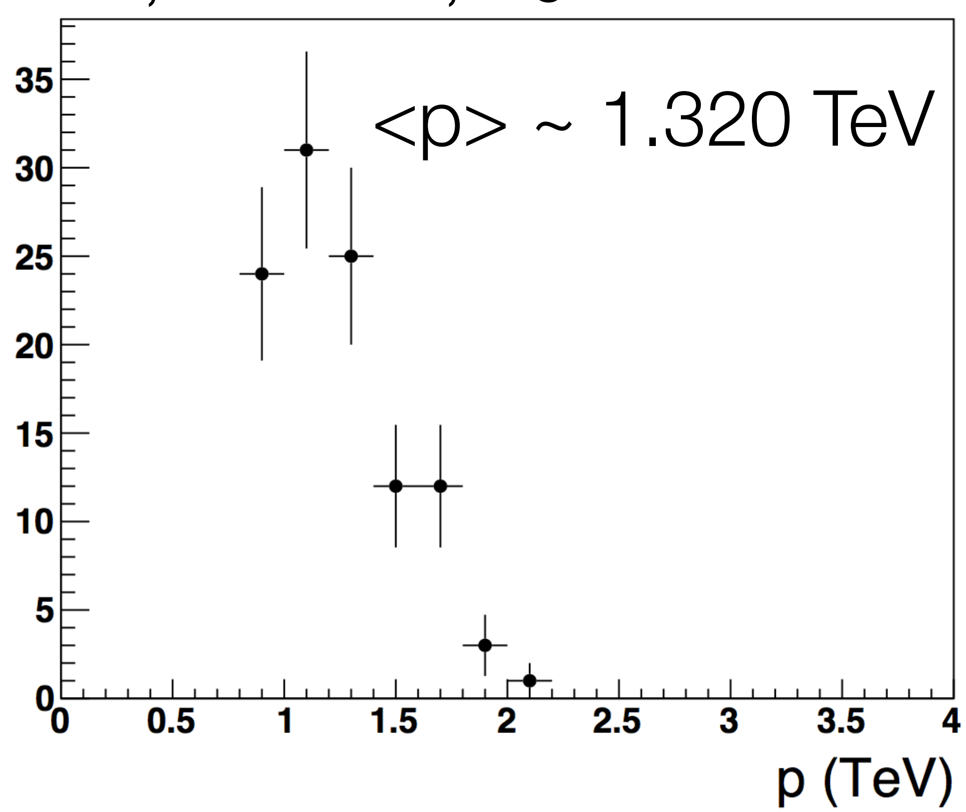
- Channeled baryons have high momentum ≥1 TeV/c

Λ_c^+ momentum distribution

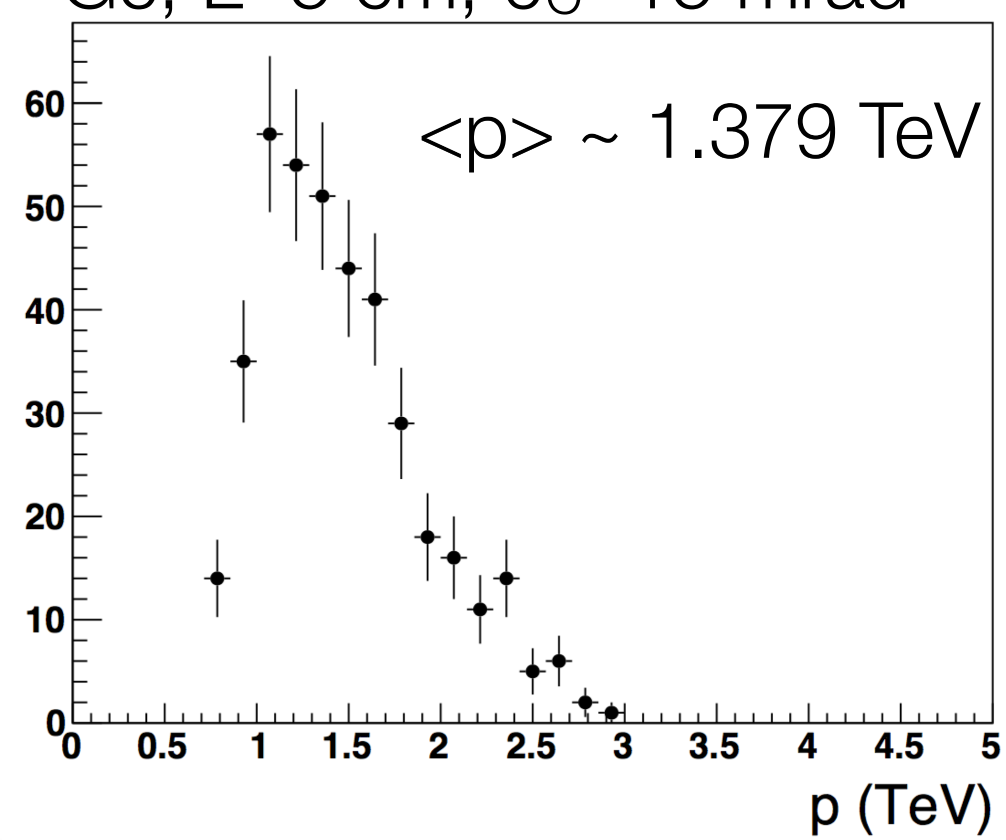


- At production (top)
- After channeling and p>800 GeV/c (bottom)

Si, L~7 cm, θ_C~14 mrad



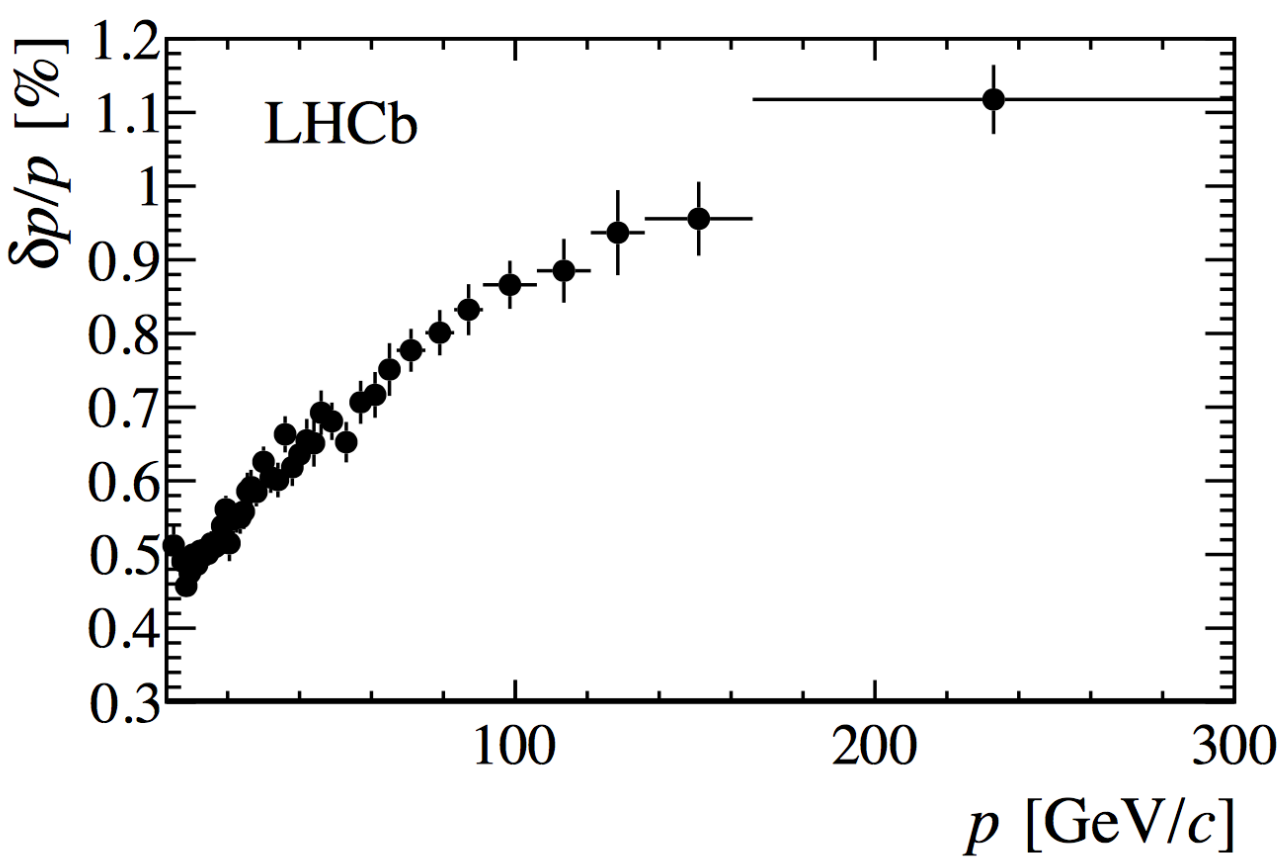
Ge, L~5 cm, θ_C~15 mrad



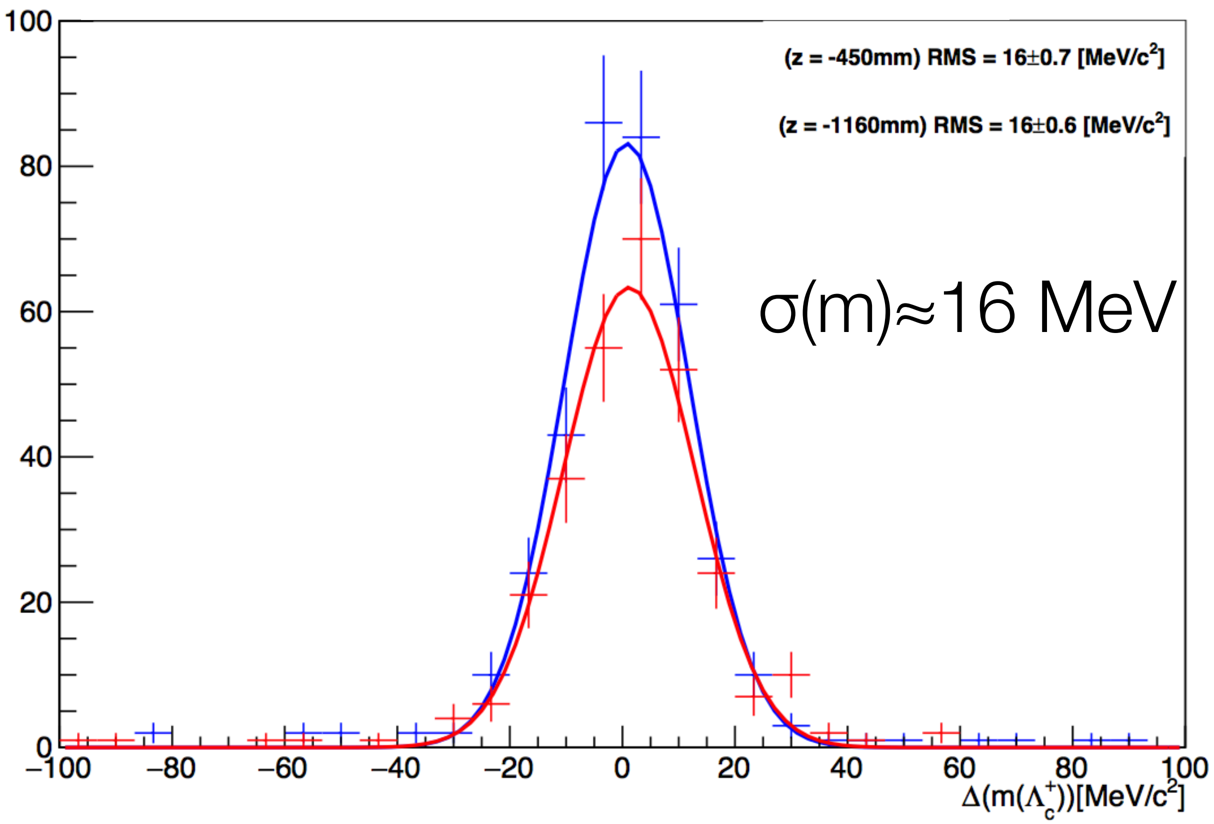
Signal reconstruction

- $\Lambda_c^+ \to pK^-\pi^+$ daughter particles (p≳300 GeV/c) have reduced momentum resolution ≳1%

Int. J. Mod. Phys. A 30, 1530022 (2015)



$p(\Lambda_c)$=1 TeV/c

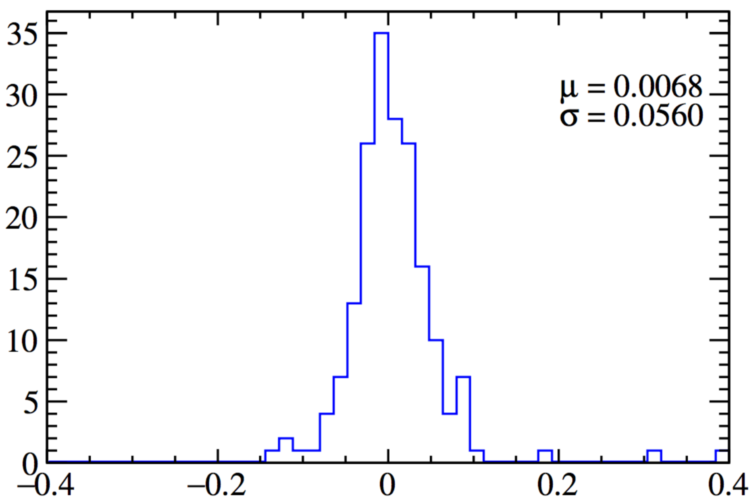


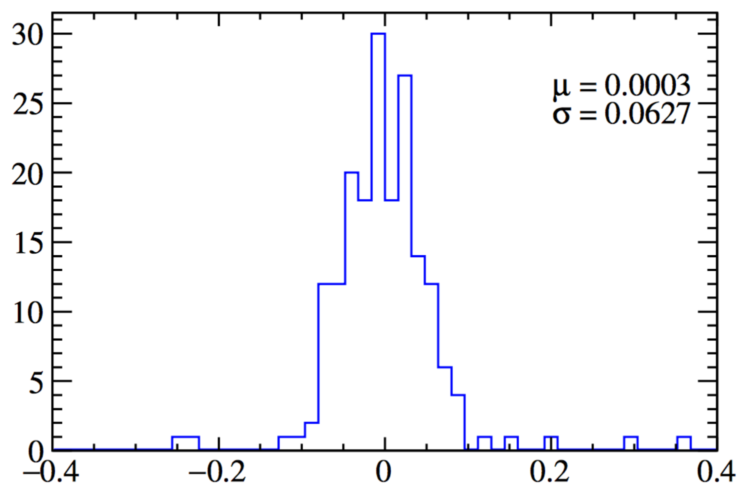
- Invariant mass resolution 16 MeV is good enough for signal reconstruction and background rejection

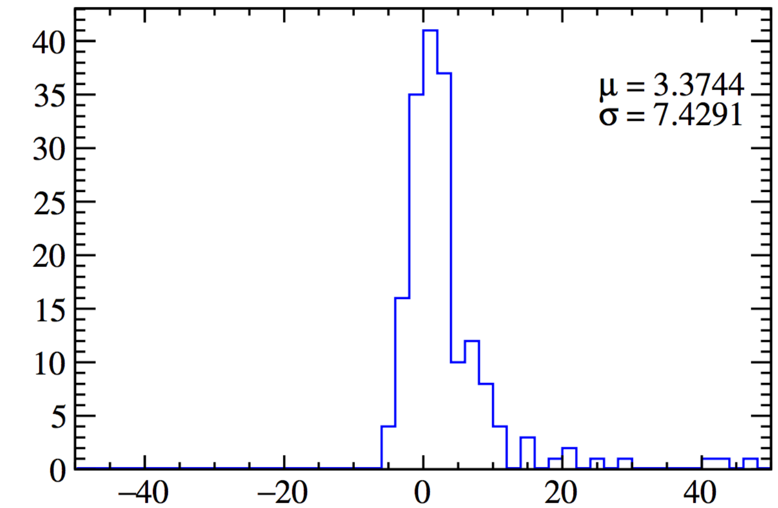
Vertex resolution

- Primary vertex resolution (minimum bias events)

$\sigma(PV_x)\sim 60\mu m$ $\sigma(PV_y)\sim 60\mu m$ $\sigma(PV_z)\sim 7.4$ mm

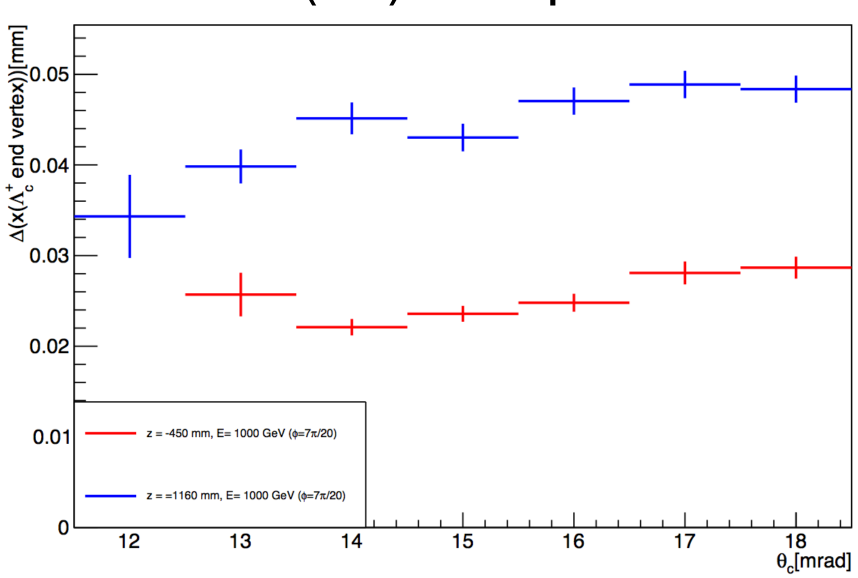


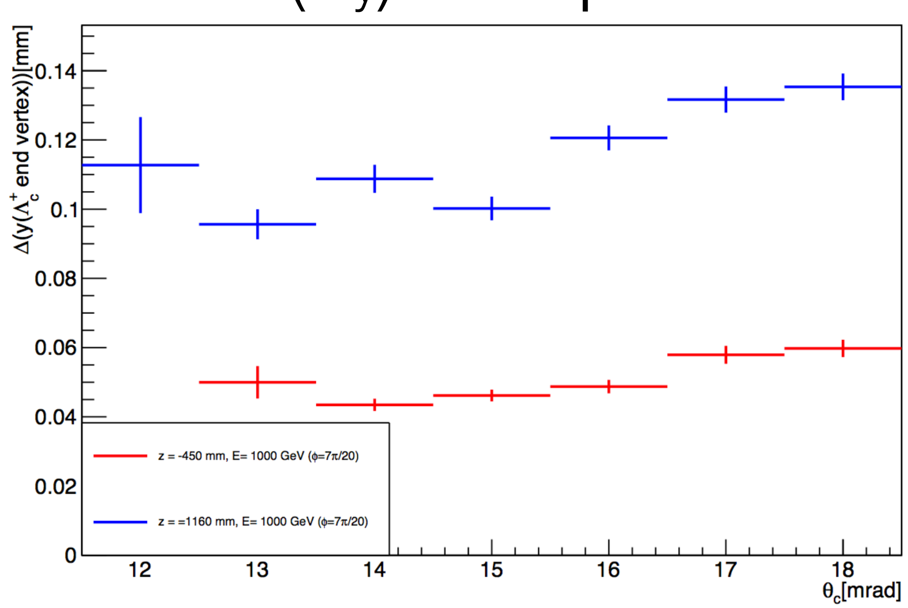


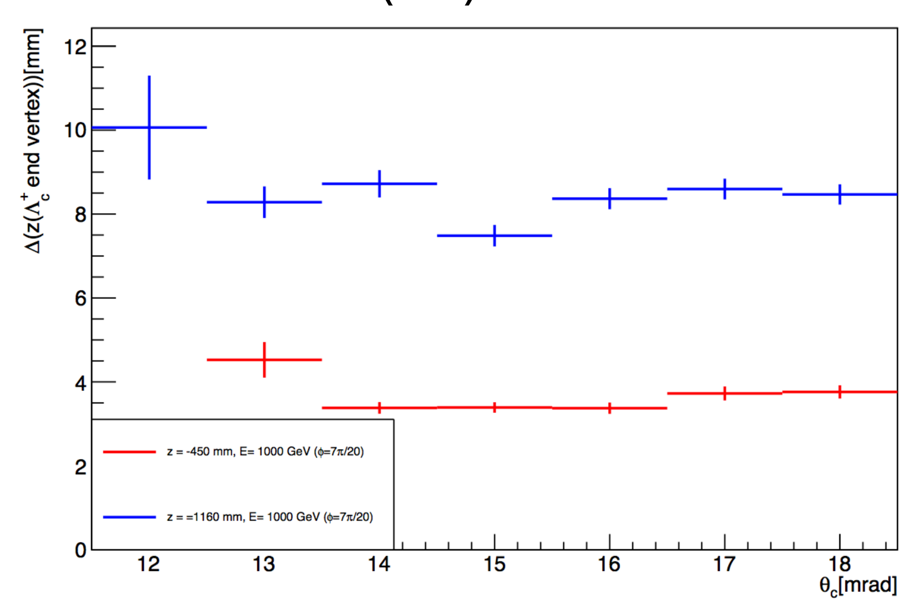


- Secondary vertex resolution vs bending angle

$\sigma(V_x)\sim 40\mu m$ $\sigma(V_y)\sim 100\mu m$ $\sigma(V_z)\sim 8mm$

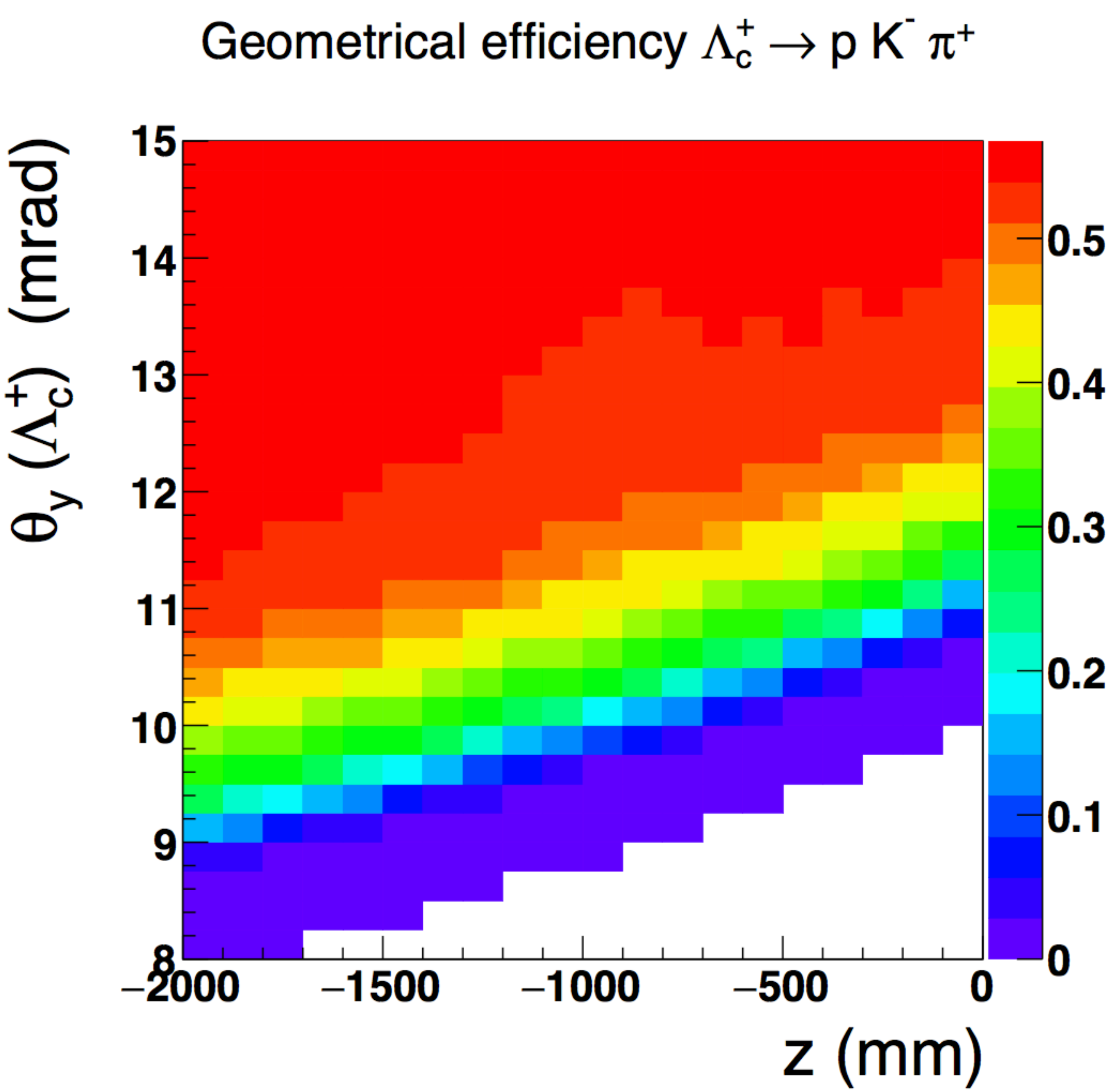


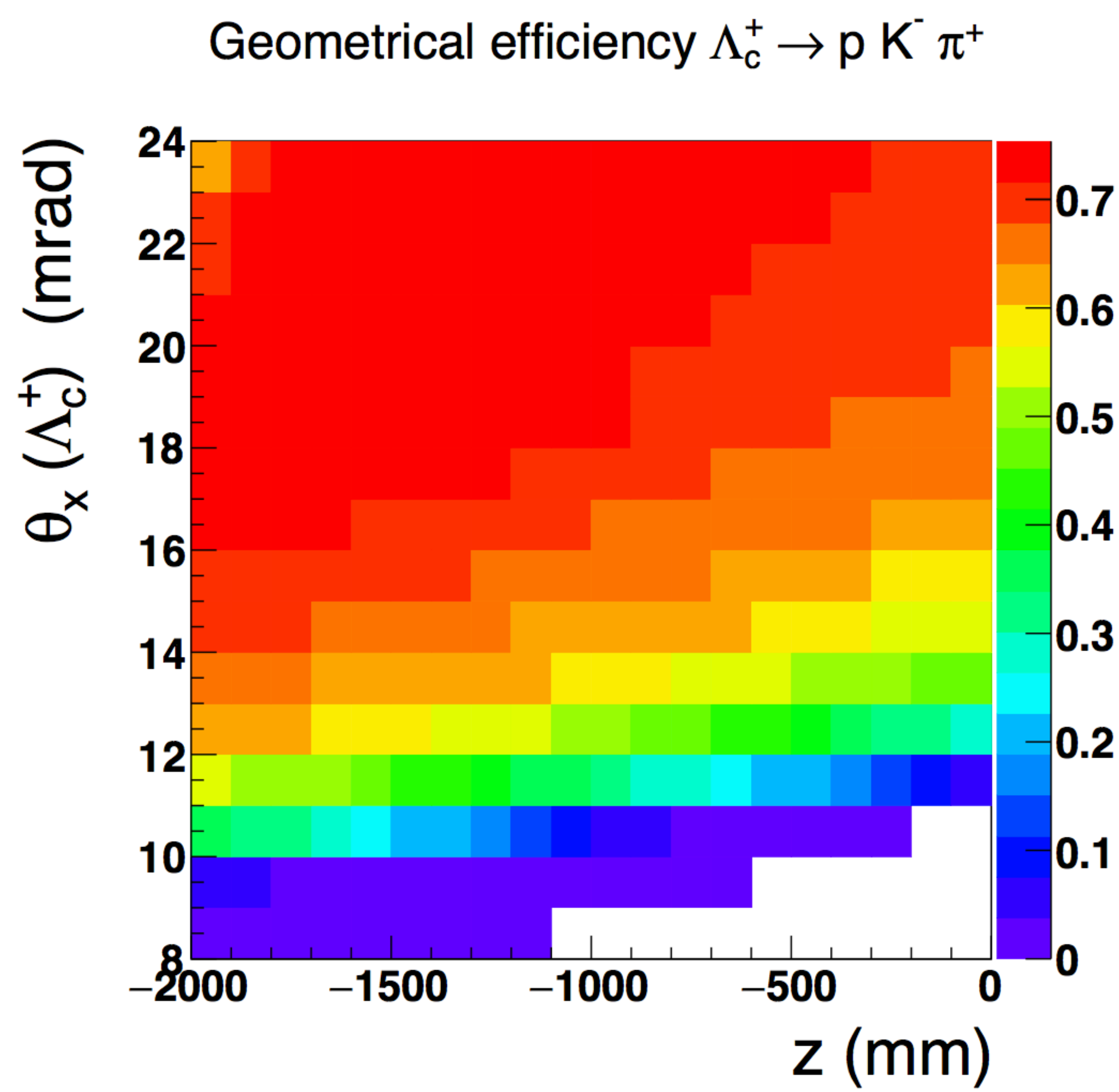




Geometrical efficiency

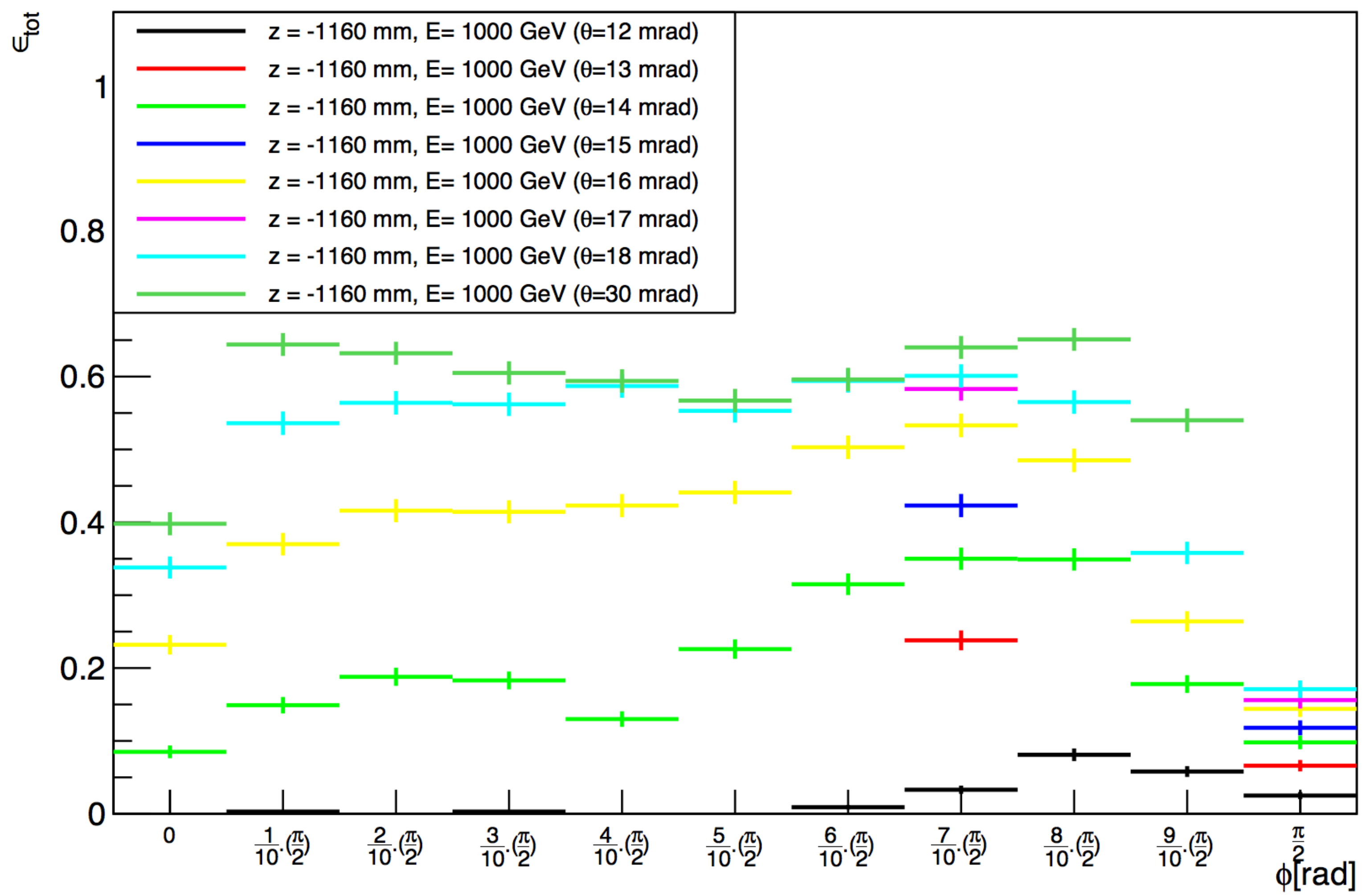
- Due to LHCb detector acceptance a relative large bending angle is required

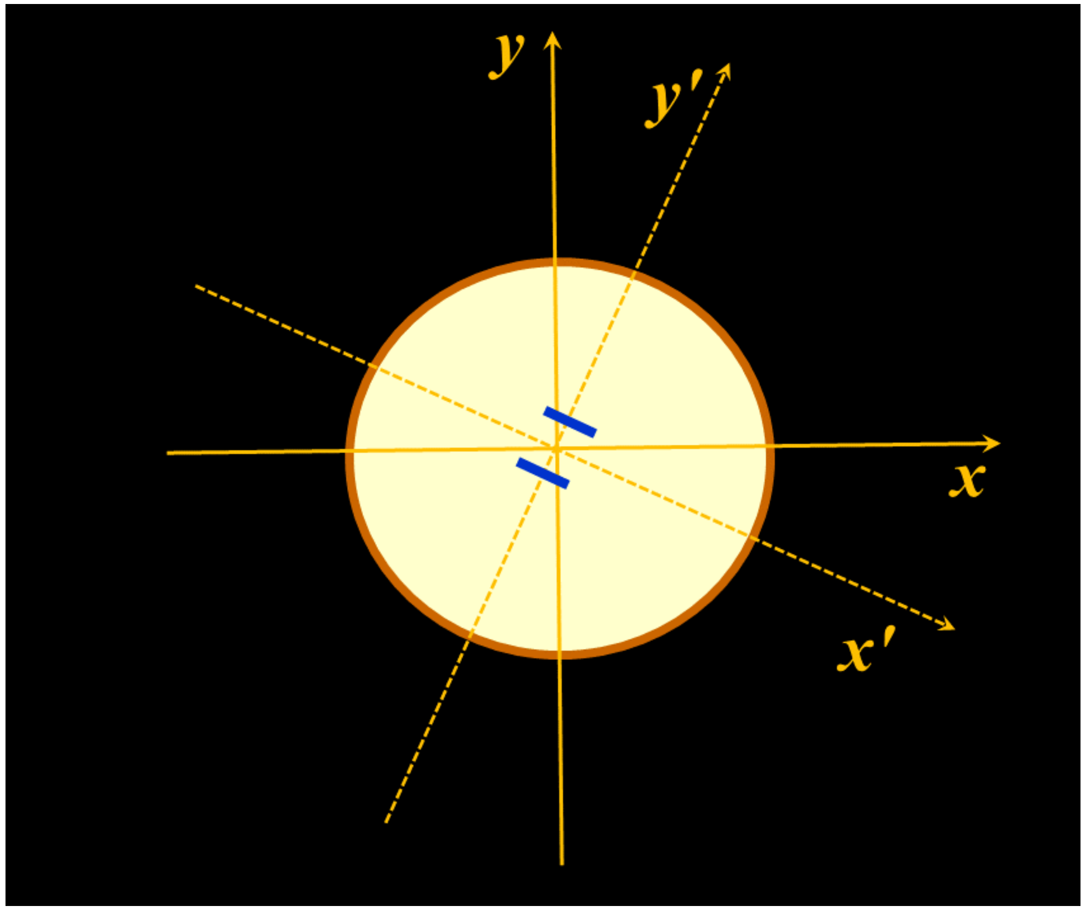




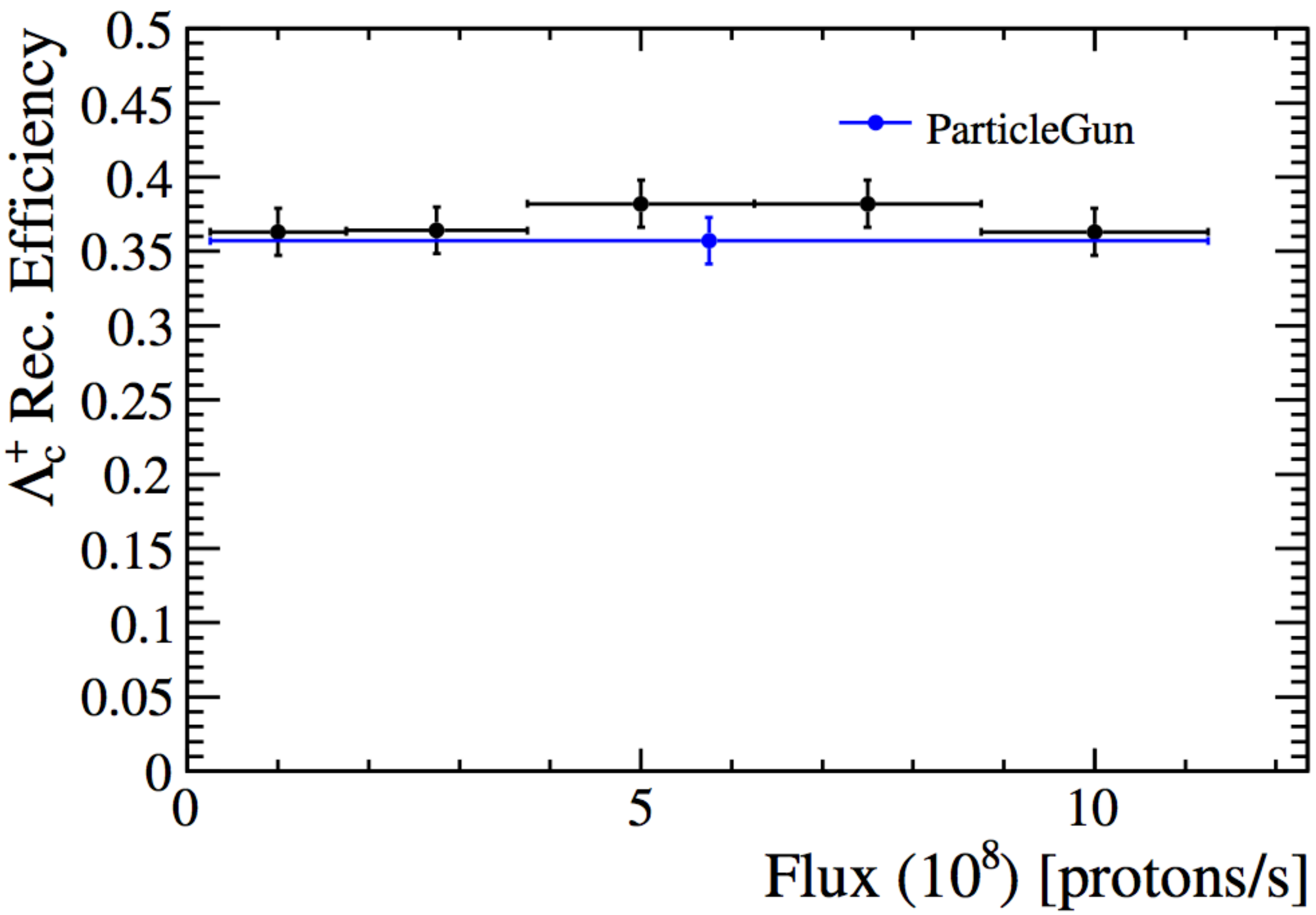
Reconstruction efficiency

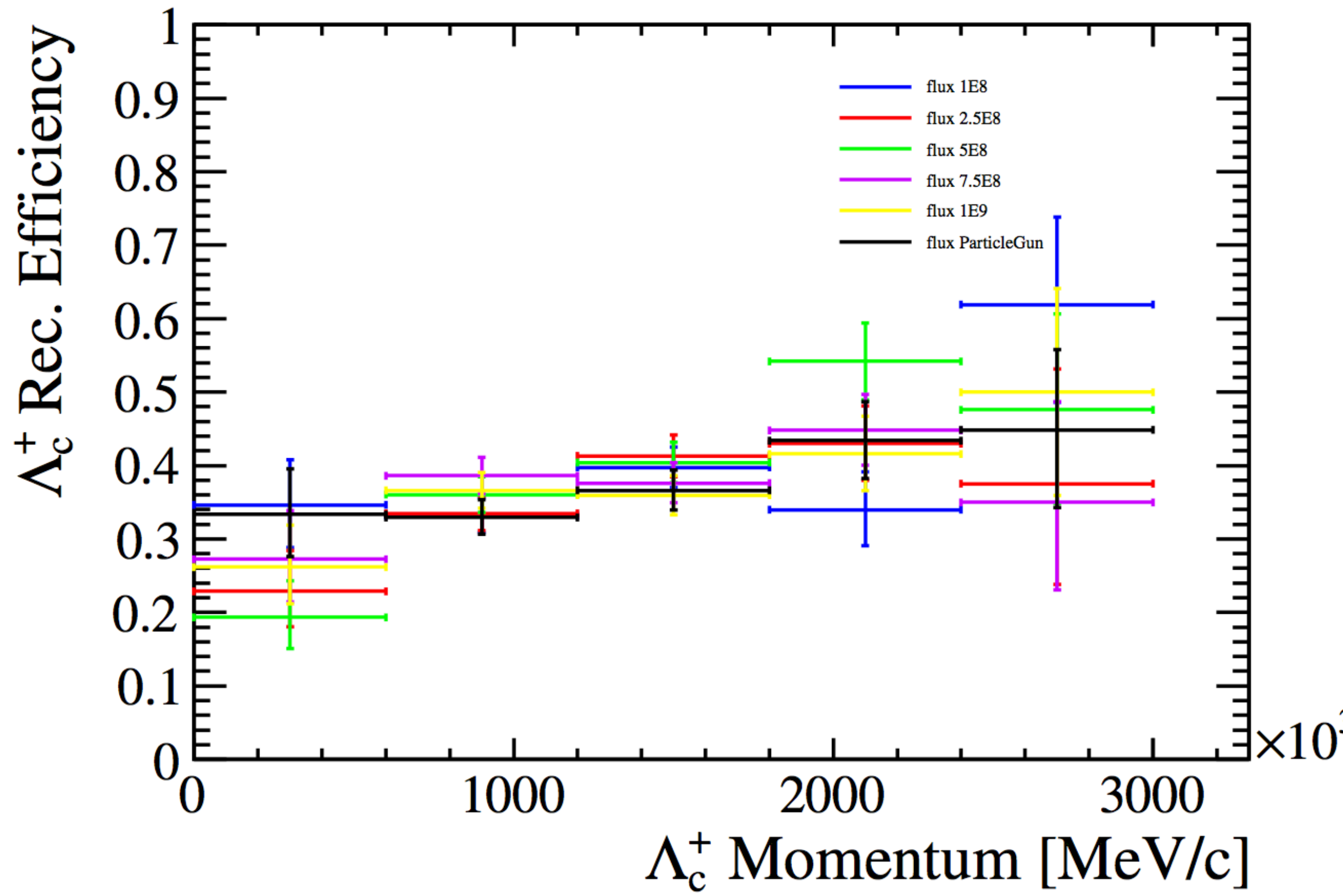
- Efficiency vs target azimuthal angle: max at 7/10 π. Effect due to SciFi detector acceptance
- Reco efficiency of 40% with 15 mrad bending angle





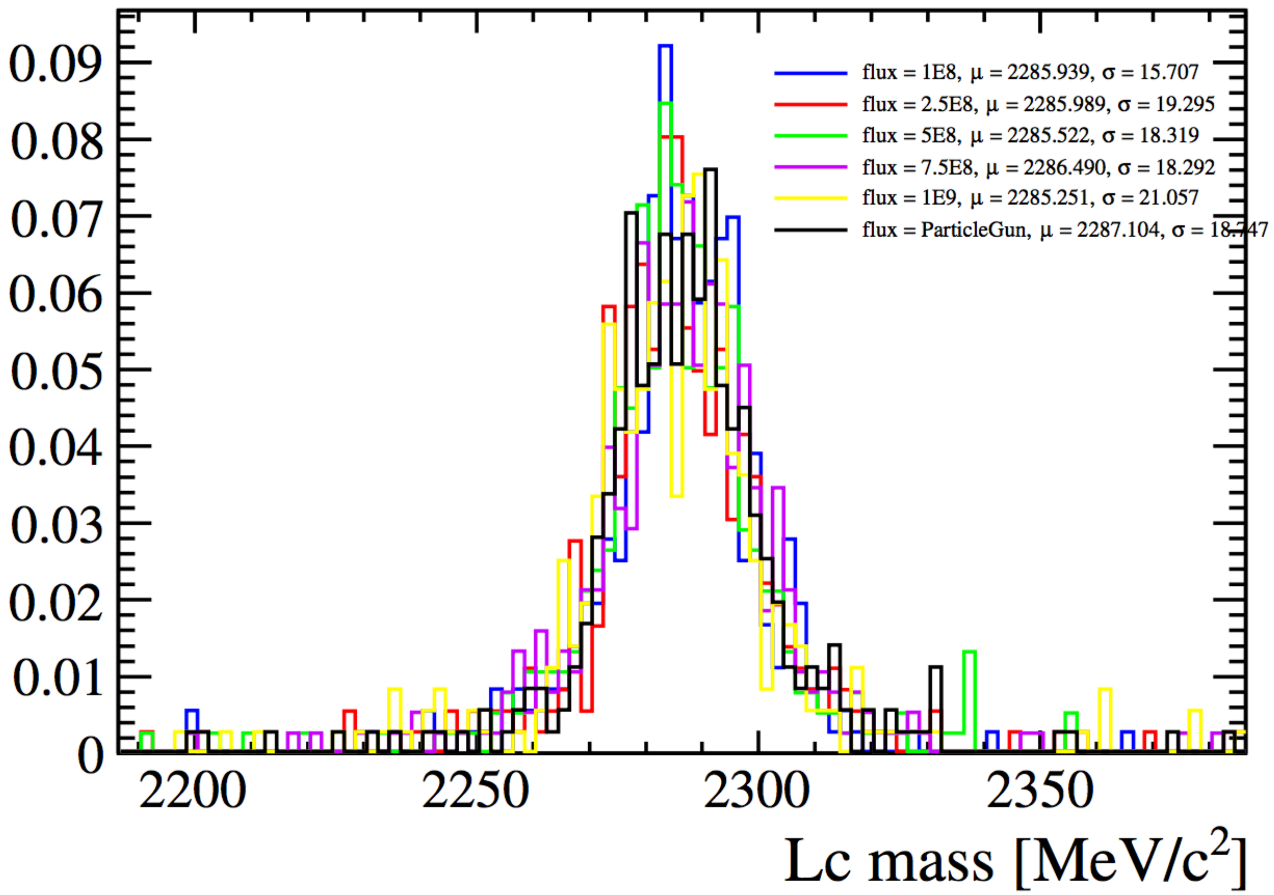
Efficiency vs proton flux

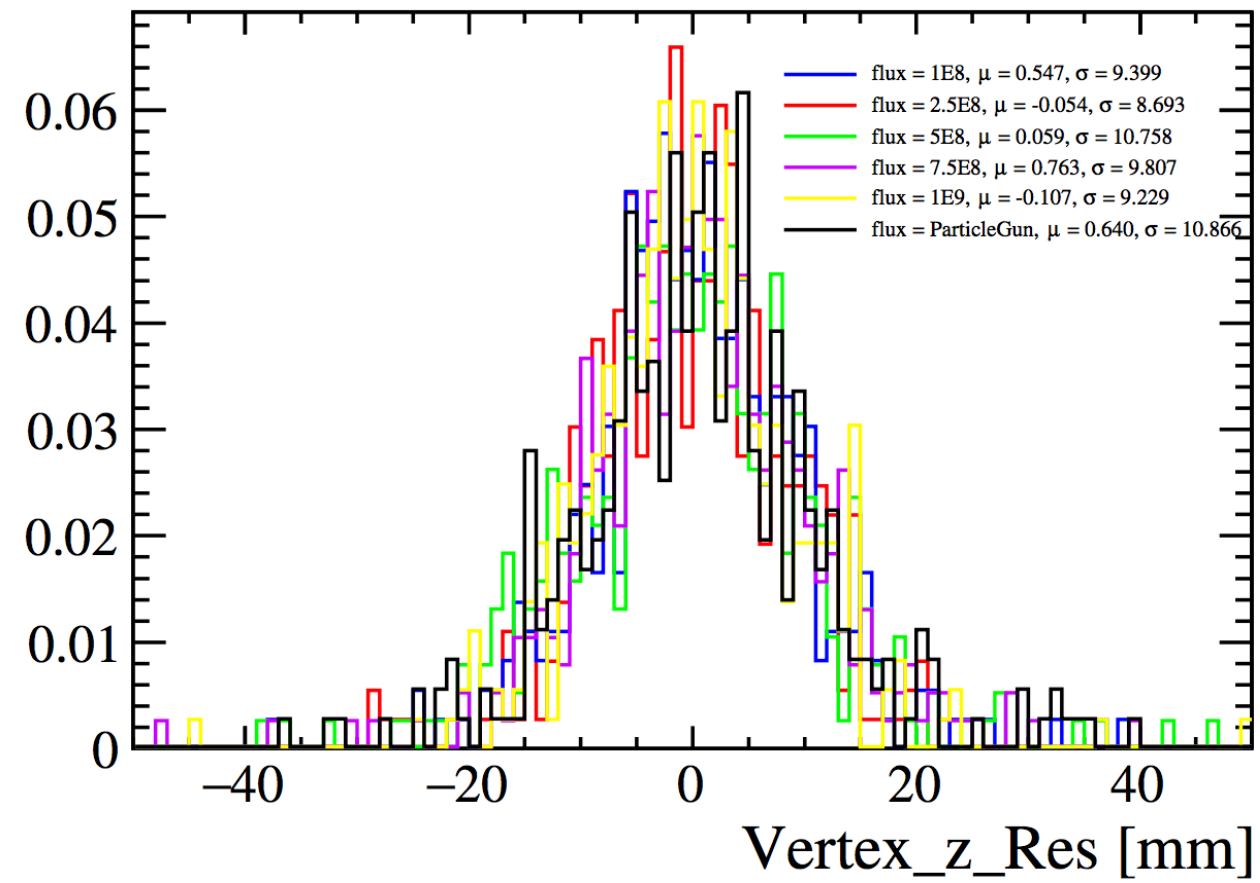




- Good reconstruction efficiency up to 10^9 p/s
- Possibility to increase flux in dedicated runs

Resolution vs proton flux

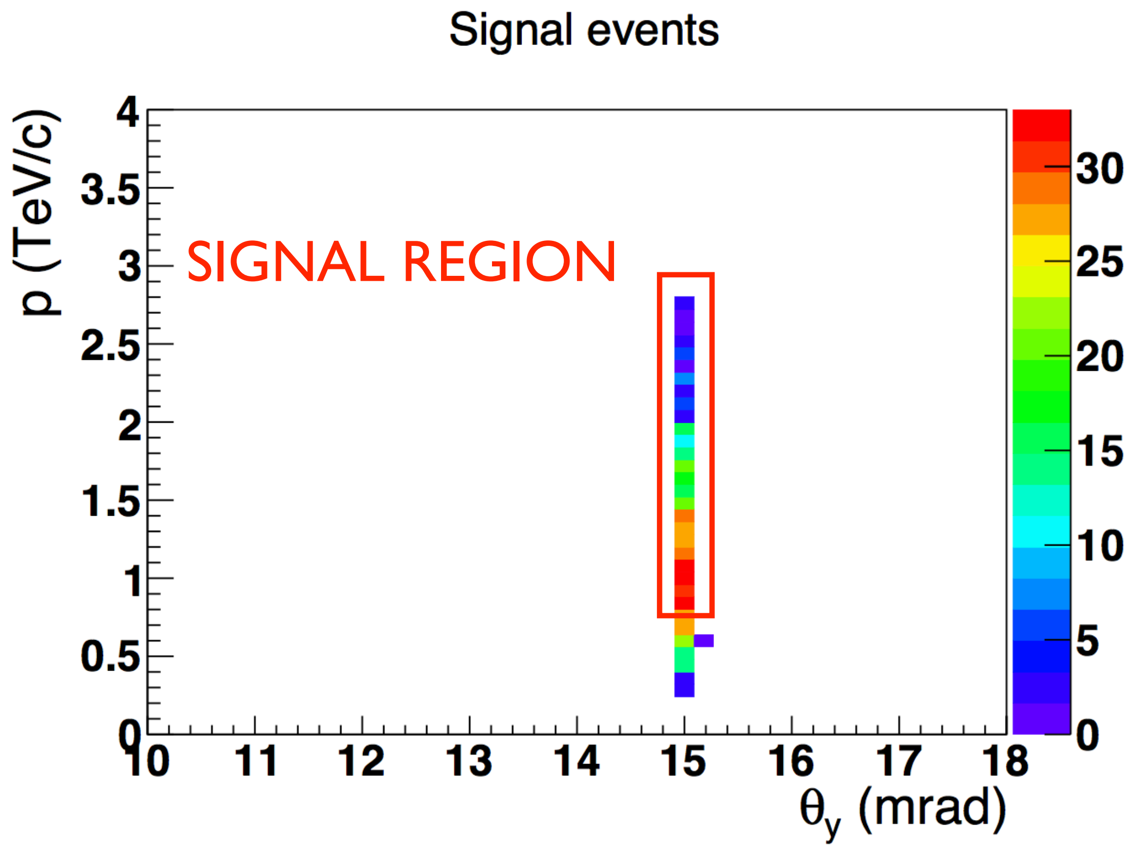




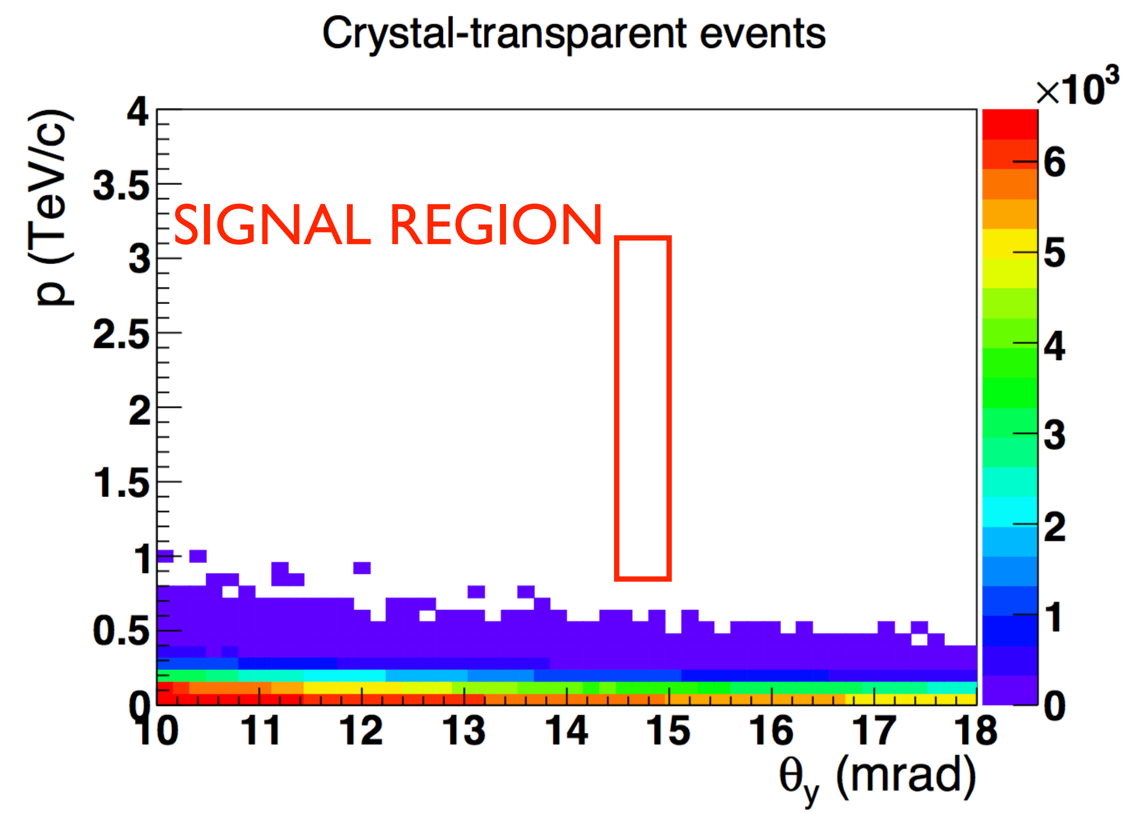
- Λ_c^+ mass and z decay vertex resolution vs proton flux

Background rejection

- Rejection of unchanneled Λ_c^+ produced in W target



Channeled particles

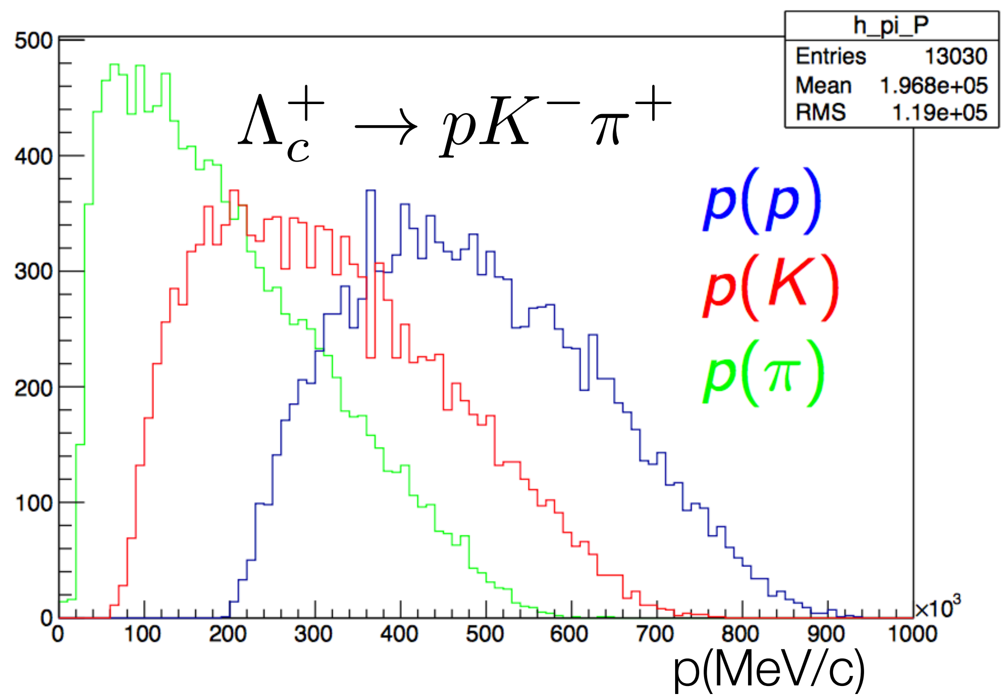


Unchanneled particles

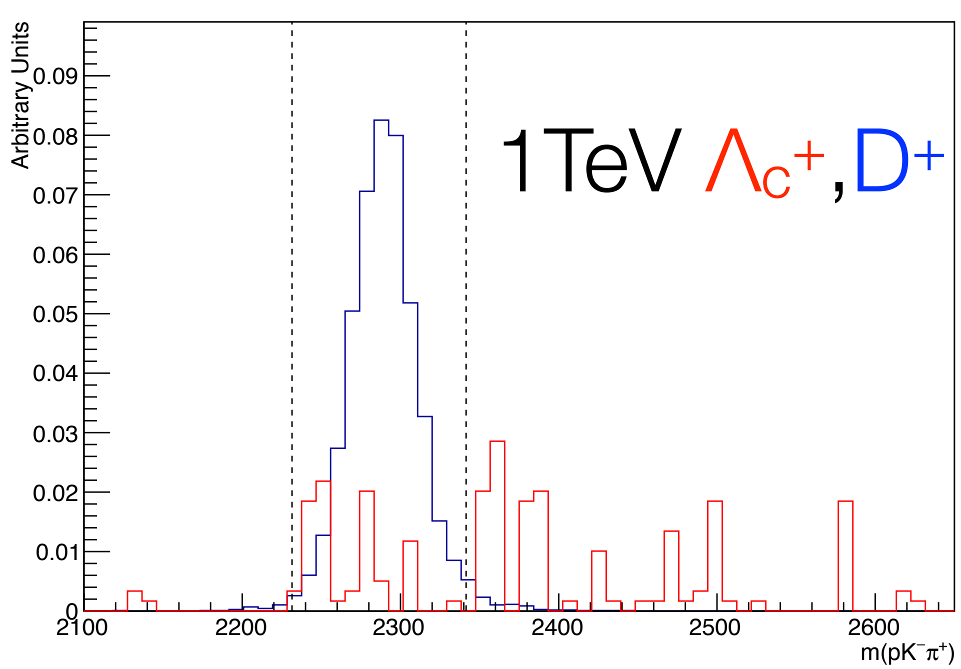
- Signal region: $14.8<\theta<15.2$ mrad [$\sigma(\theta)$~25μrad], $p_{\Lambda c}> 800$ GeV/c
- Background rejection 10^{-7} level and signal efficiency 80%
- High momentum Λ_c^+ most sensitive for EDM measurements

Background rejection

- Rejection of charm background, e.g. $D^+ \to K^-\pi^+\pi^-$, $D_s^+ \to K^-K^+\pi^-$ based on kinematic information only



Production and BR normalized Λ_c^+ and D^+ distributions

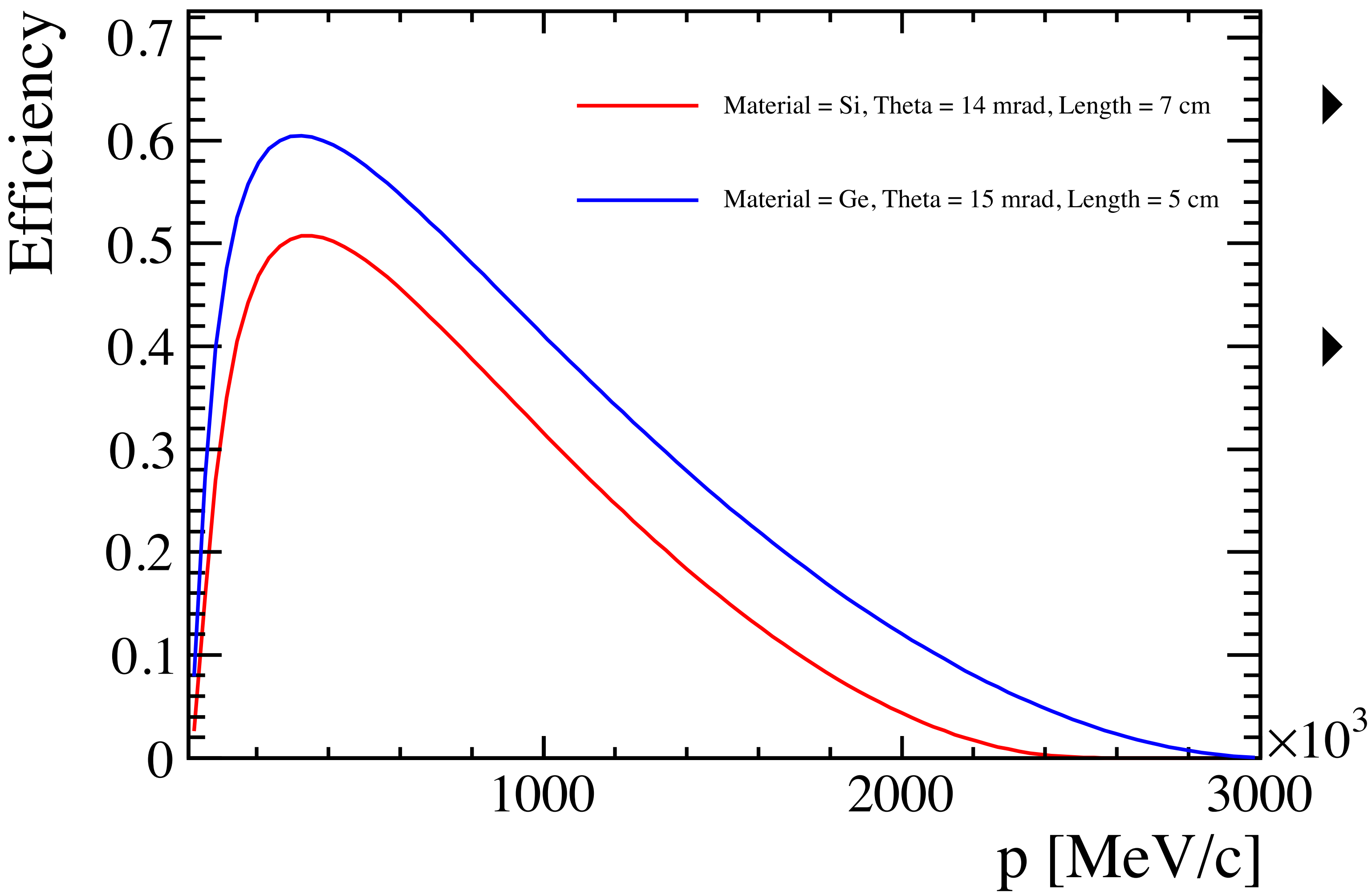


- Particle mass hypothesis based on momentum hierarchy: highest proton, second K^- and then π^+
- Efficiency for signal events ~90%, negligible reflections from signal
- Veto reflections from $D^+ \to K^-\pi^+\pi^-$, $D^+ \to K^-K^+\pi^-$ events by invariant mass cut with different mass hypothesis

Identification	Fraction(%)
Signal efficiency	77.6
$D^+ \to K^-\pi^+\pi^+$ efficiency	2.4

Sensitivity studies

Channeling efficiency

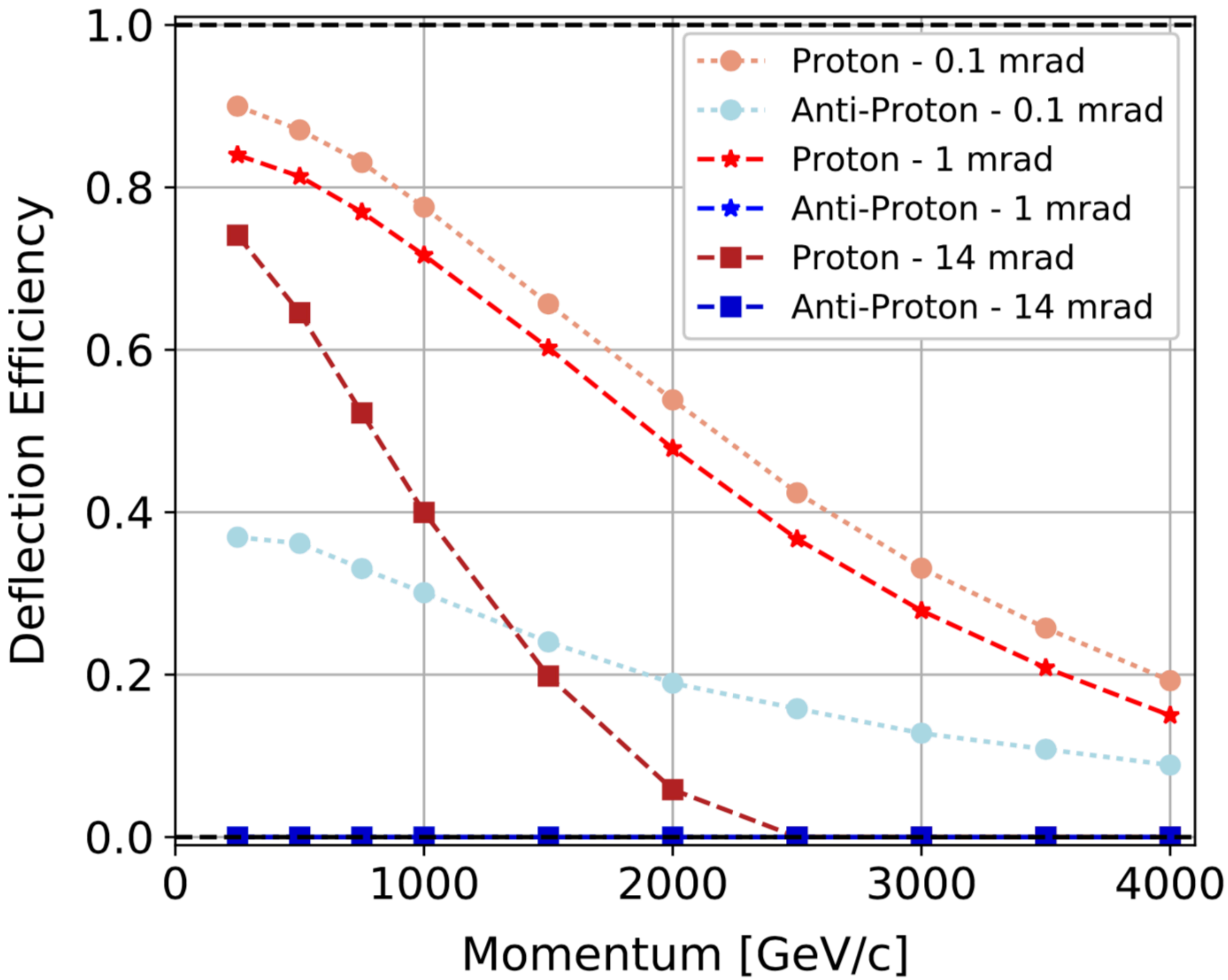


- Channeling efficiency for Λ_c^+ particles within Lindhard angle
- Total channelling efficiency: Lindhard angle, dechanneling, Λ_c^+ decay flight: $1 \cdot 10^{-5}$ (Si), $4 \cdot 10^{-5}$ (Ge)

$$w(\theta_C, R) = \left(1 - \frac{R_c}{R}\right)^2 \exp\left(-\frac{\theta_C}{\theta_D \frac{R_c}{R}(1 - \frac{R_c}{R})^2}\right)$$

- Parametrisation from Biryukov, Valery M. (et al.), *Crystal Channeling and Its Application at High-Energy Accelerators*, Springer Verlag (1997)

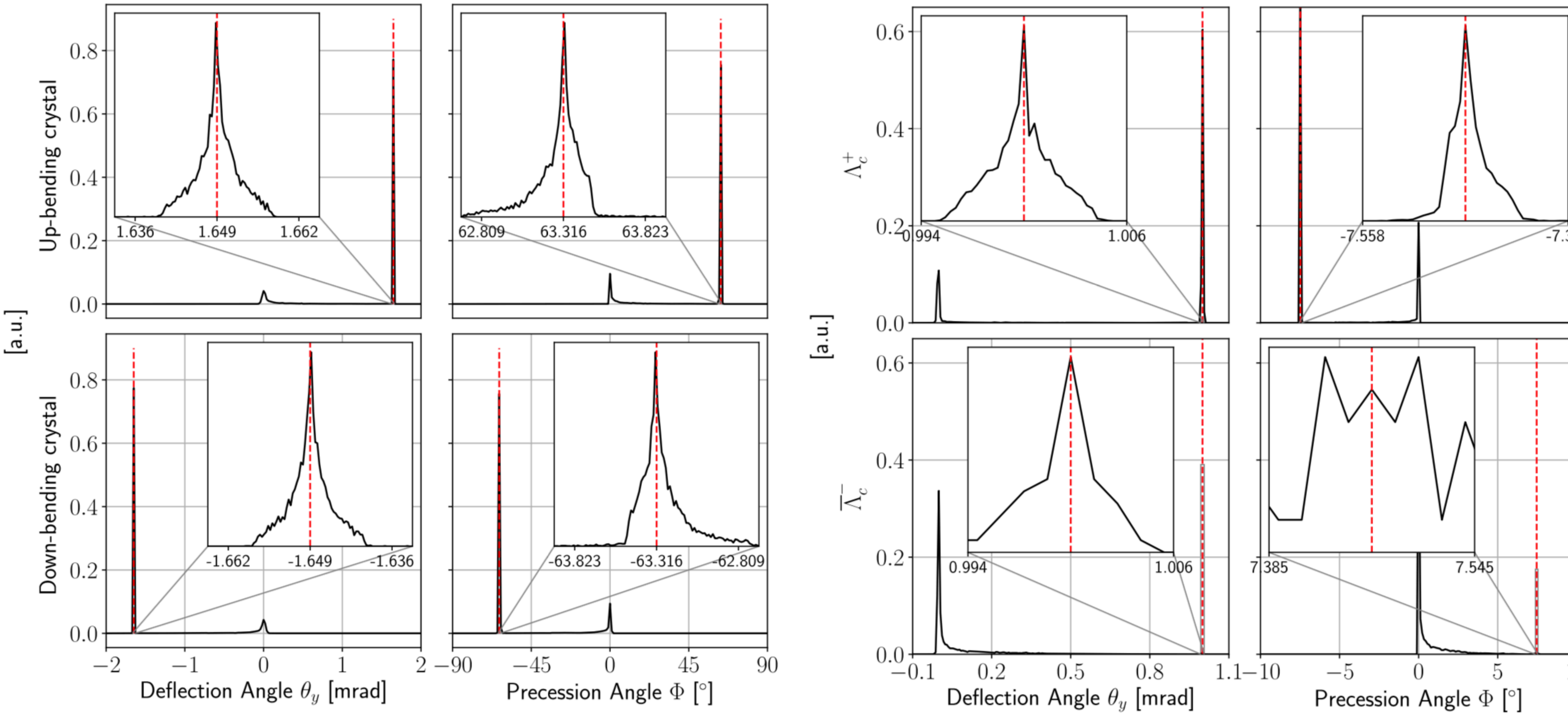
Channeling efficiency



Channeling efficiency for protons and antiprotons for 1mm (0.1mrad), 1cm (1mrad), and 7cm (14mrad) Silicon crystal

EPJC (2017) 77:828

Spin precession in bent crystal



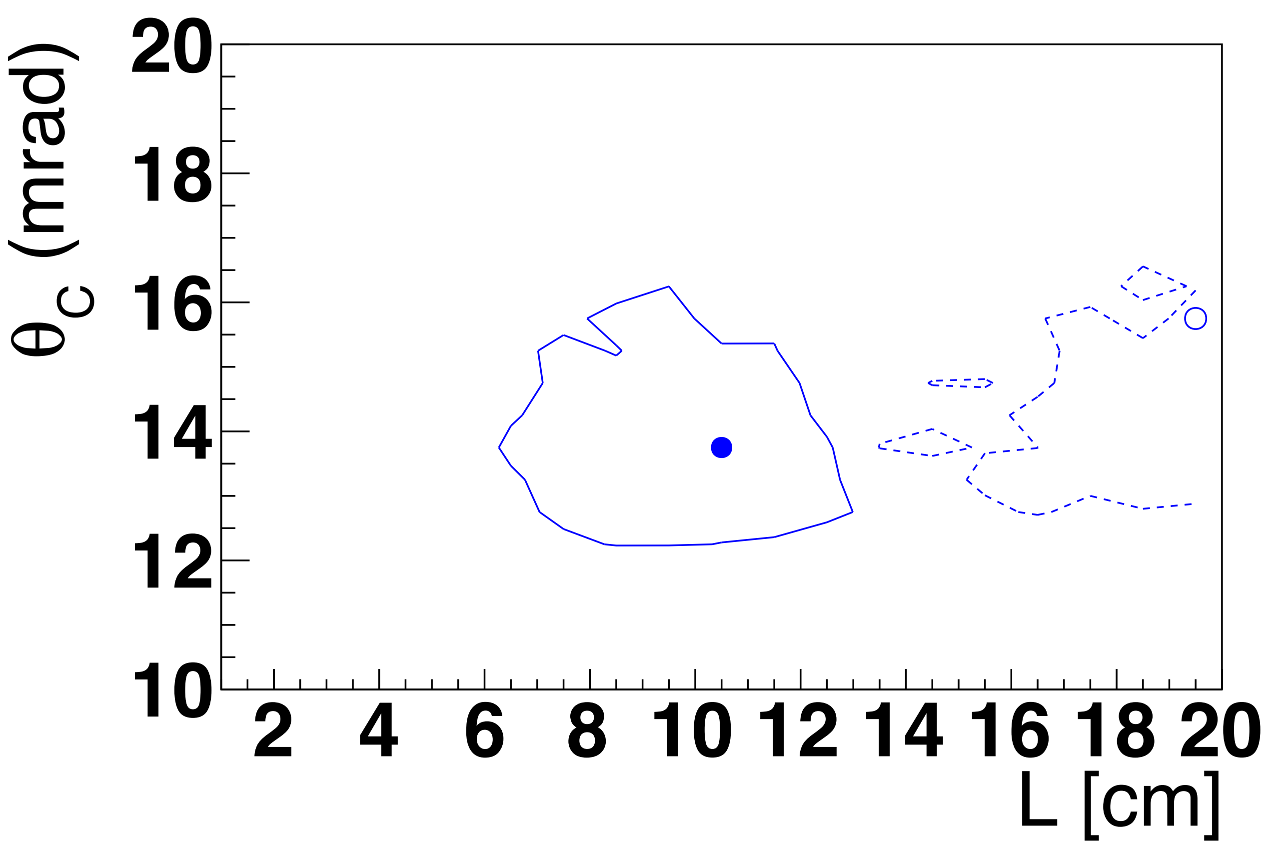
EPJC (2017) 77:828

- GEANT4 simulation of spin precession inside crystal in agreement with analytical calculations

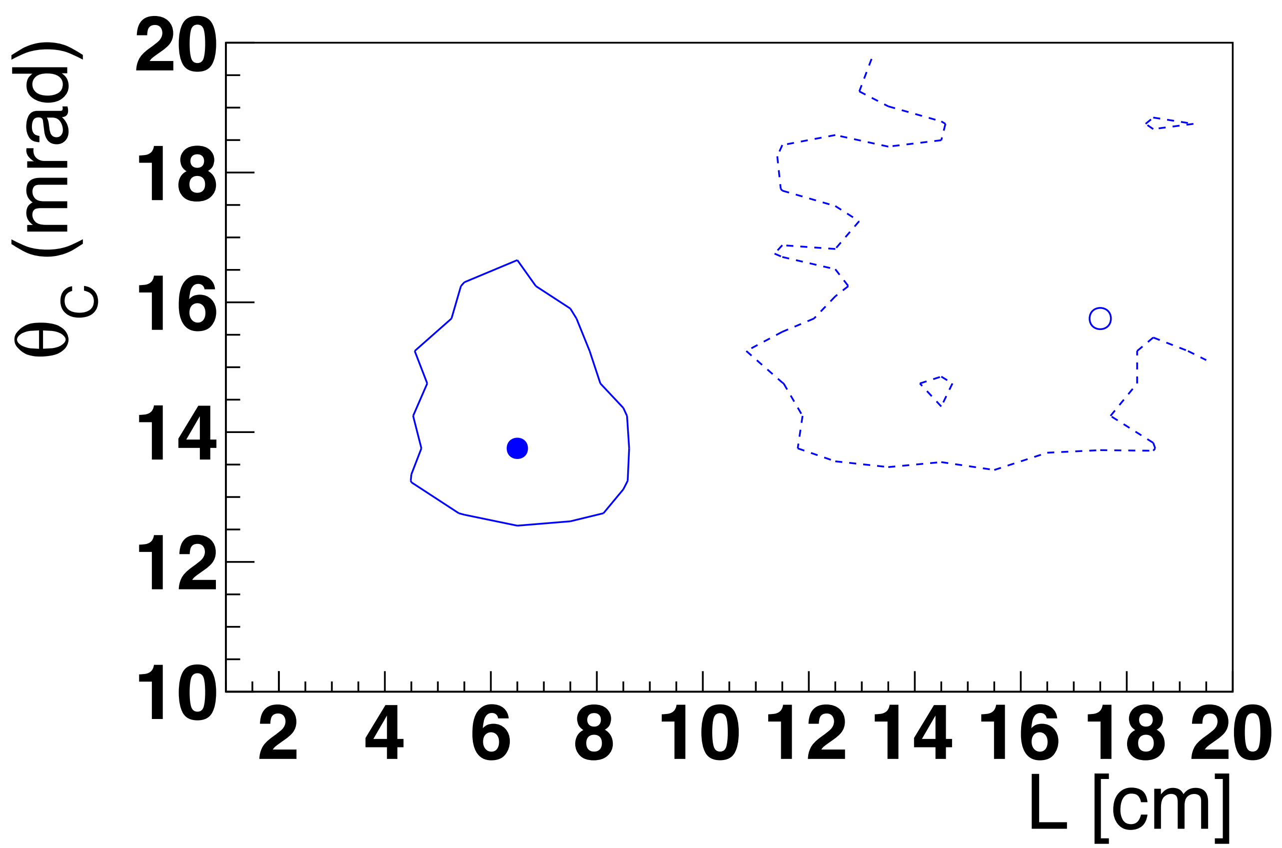
Crystal optimisation

- Optimised sensitivity to EDM and MDM.
  Channeling and reconstruction efficiency included

Si crystal

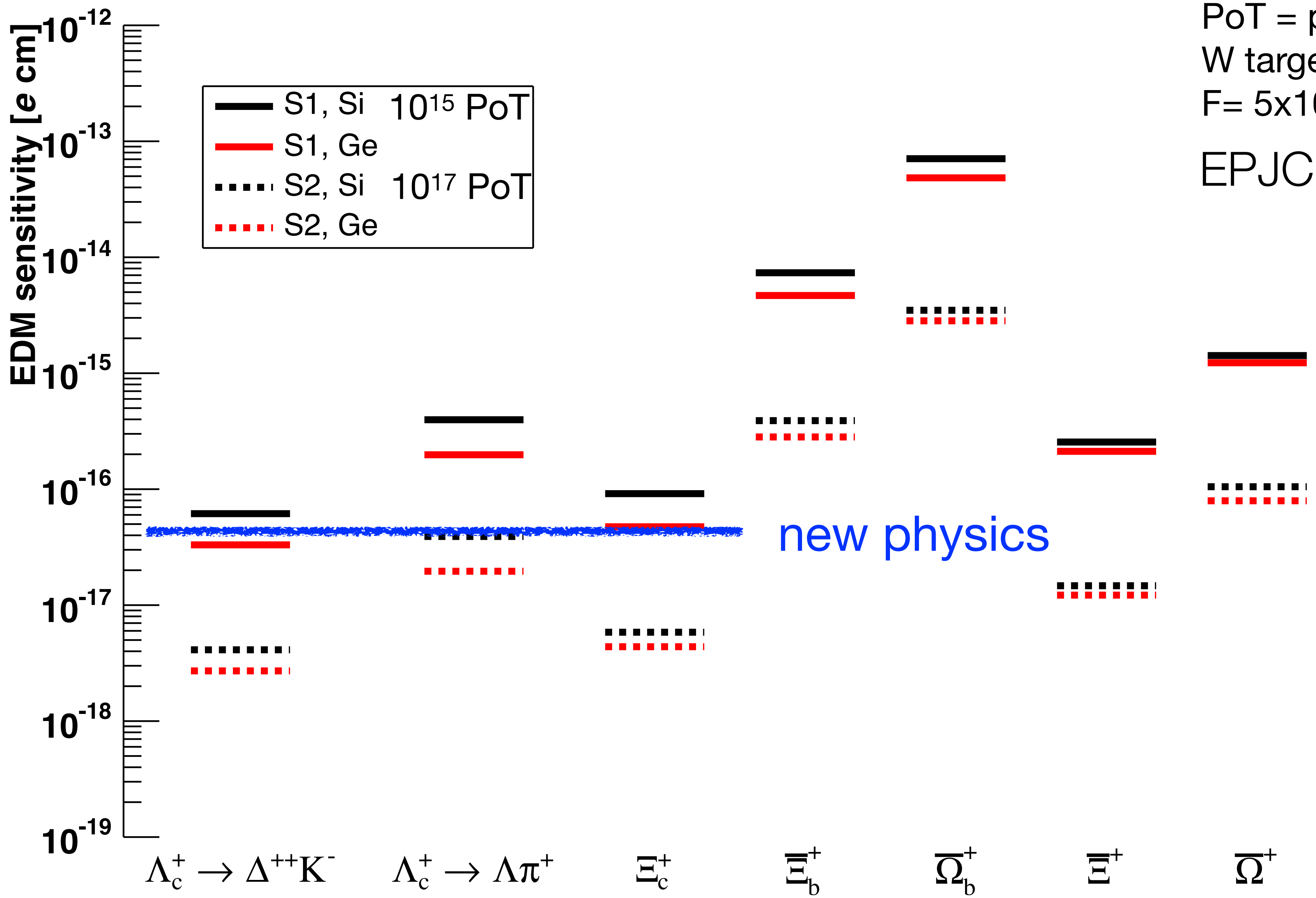


Ge crystal



Regions of minimal uncertainty of EDM (continuous line) and MDM (dotted line) defined as +20% uncertainty with respect to the minimum (point marker)

Sensitivity on EDM

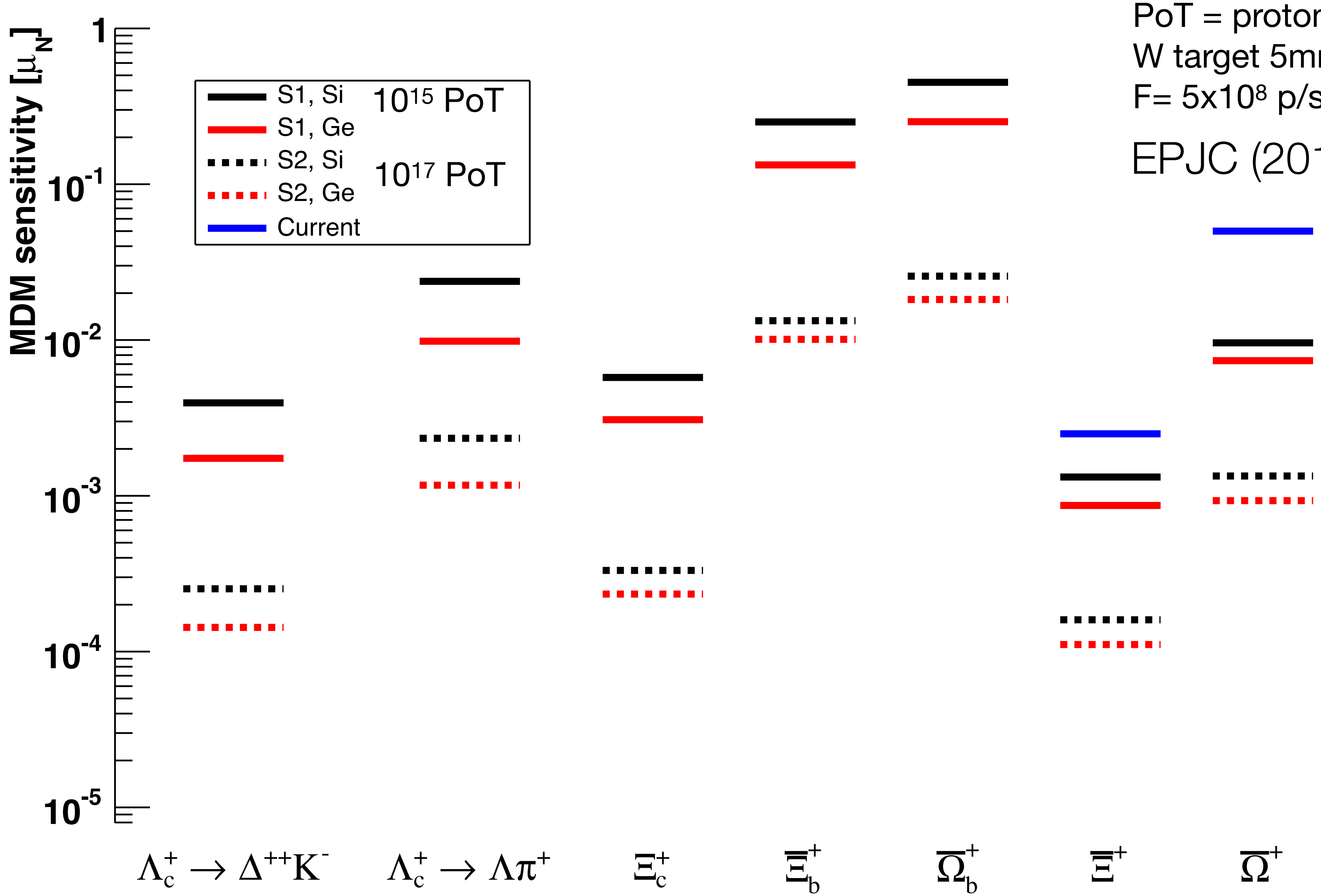


PoT = proton on target
W target 5mm thick
F= 5x10^8 p/s for S1

EPJC (2017) 77:828

- All first measurements with sensitivities capable to test new physics models

Sensitivity on MDM

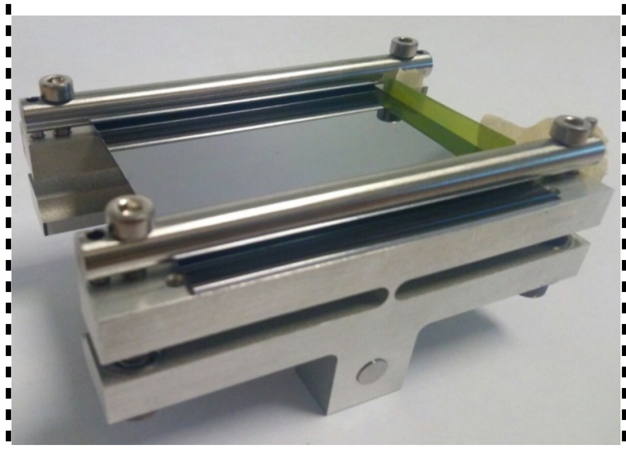
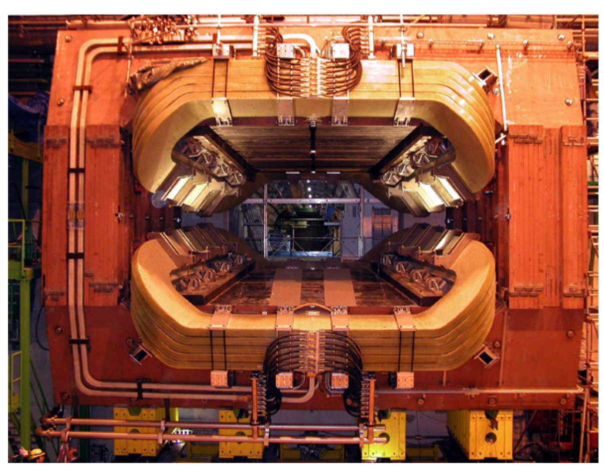


PoT = proton on target
W target 5mm thick
F= 5×10^8 p/s for S1

EPJC (2017) 77:828

- First MDM measurements. Possibility to study the spin structure of heavy baryons

Challenges and preliminary results

Baryon	**Solution**	**Challenge**	**Preliminary**
Charm Λ_c^+, Ξ_c^+ lifetime ~10^{-13} s		‣ Fixed-target setup ‣ Bent crystals with large bending angle (≳10 mrad)	✓Crystal kicker tested in LHC ✓Simulations ✓Event reconstruction ✓EPJC (2017) 77:828 New
Strange Λ lifetime ~10^{-10} s		‣ Reconstruction of long-lived Λ baryons after magnet	✓Simulations ✓Kinematic constraints from entire decay chain ✓Λ decay vertex

Installation and operations

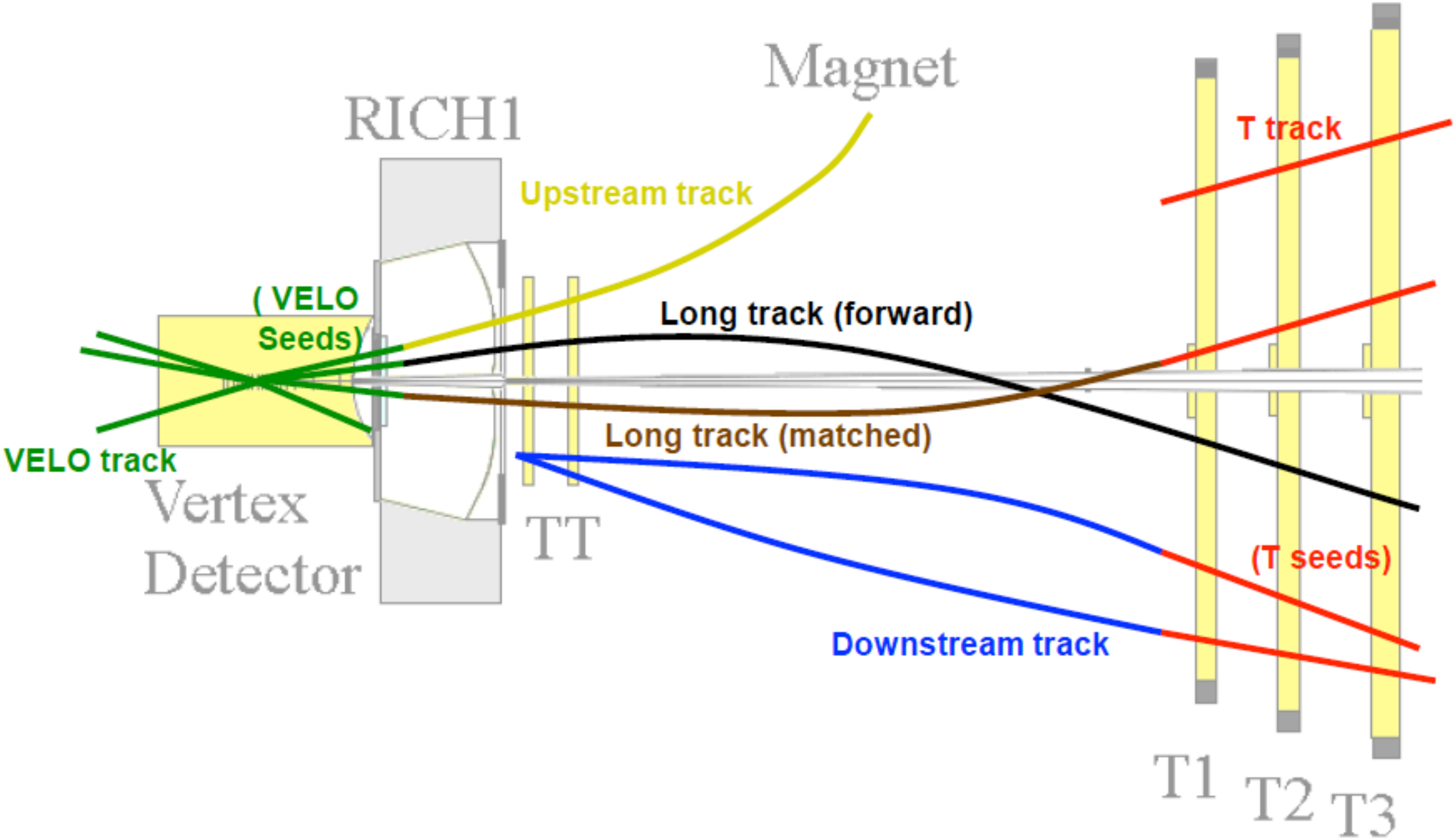
- Installation during EYETS after LS2:
  - crystal kicker installation in LHC ~1-2 days. Designed by CERN and produced by a company
  - W target + bent crystal in front of the LHCb detector at z=-116cm. Outside the VELO detector vacuum vessel
- Operations: dedicated running with nominal pp collisions
  - aim at 10^{15} PoT for the EDM, MDM measurements
  - a dedicated run at 5×10^{8} p/s would take about 10 weeks, assuming 30% efficiency in data taking
  - Runs of 2 weeks/year at 5×10^{8} p/s during Run3 would allow $6 \cdot 10^{14}$ PoT by the end of 2023

Summary

- Unique experimental setup for baryon EDM/MDM measurement in LHCb was presented: feasible and suitable for dedicated runs (~2 weeks/year)
- Specifications:
  - Ge bent crystal 15 mrad, 5 cm (Si bent crystal 14 mrad, 7cm)
  - proton flux of 10^8 - 10^9 p/s
  - target position (0, 0.4, -116) cm,
  - target azimuthal angle 65 degrees
- Studies summarised in detail in a LHCb internal note. Currently under review by LHCb panel (FITPAN)

Backup slides

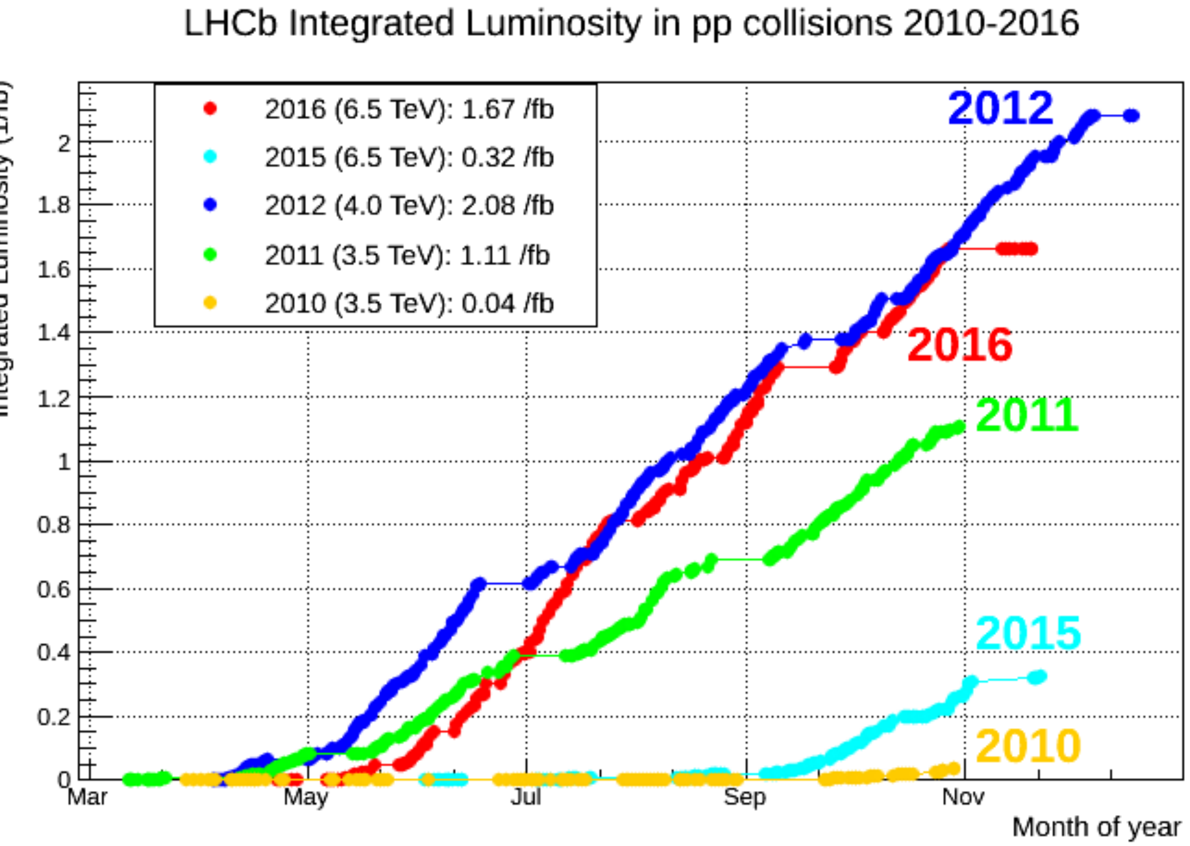
Track definitions at LHCb



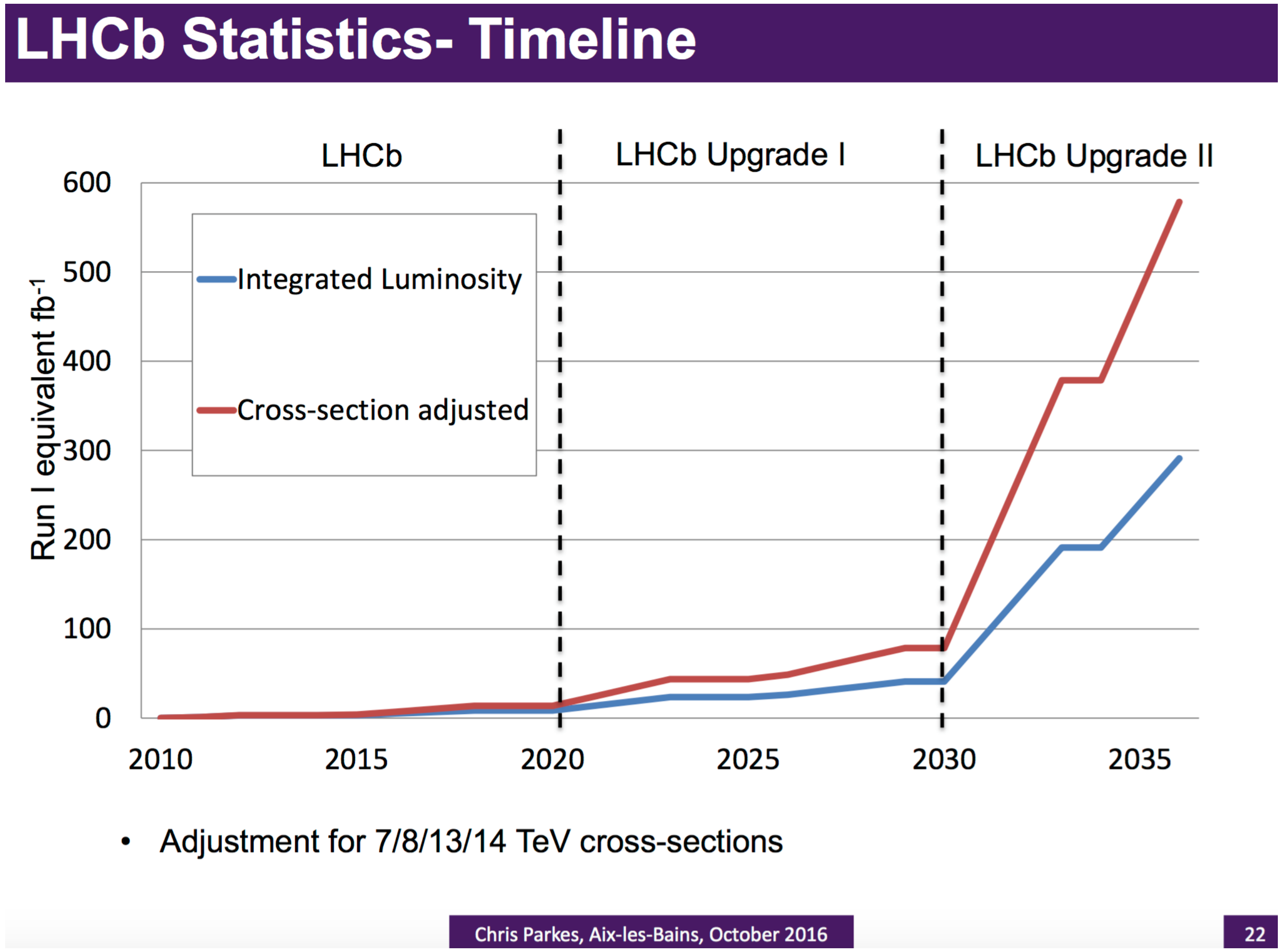
Ghost track = is a fake track. For example it can be formed by matching a real track segment in the VELO (VELO seed) with a real track segment in the downstream tracker (T seed)

LHCb statistics and perspectives

LHCb data sample



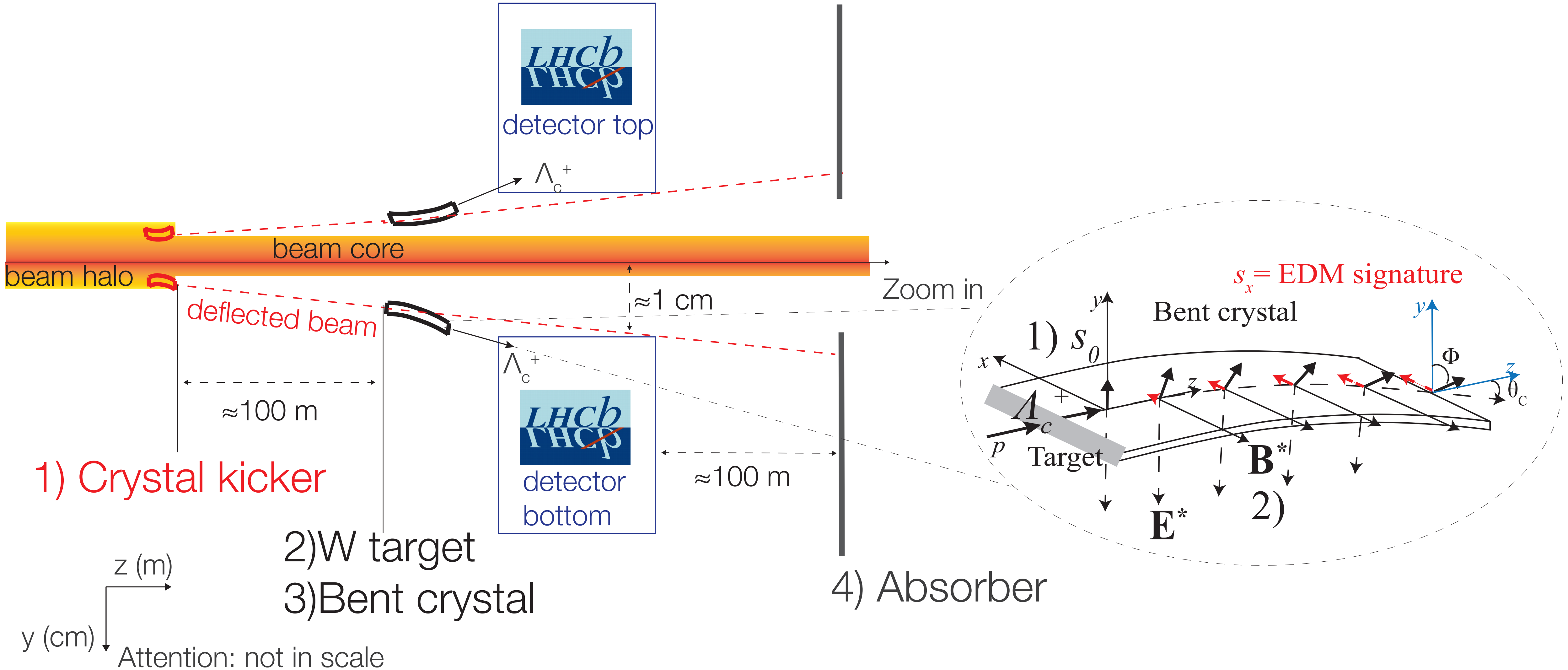
From Chris Parkes at ECFA workshop, Oct16



- In 2016 collected almost twice *b*-baryon signal yields wrt Run1, factor 2 increase in $b\bar{b}$ cross-section from 7-8TeV to 13TeV
- Possibility to increase yields x30 Upgrade I and x200 Upgrade II

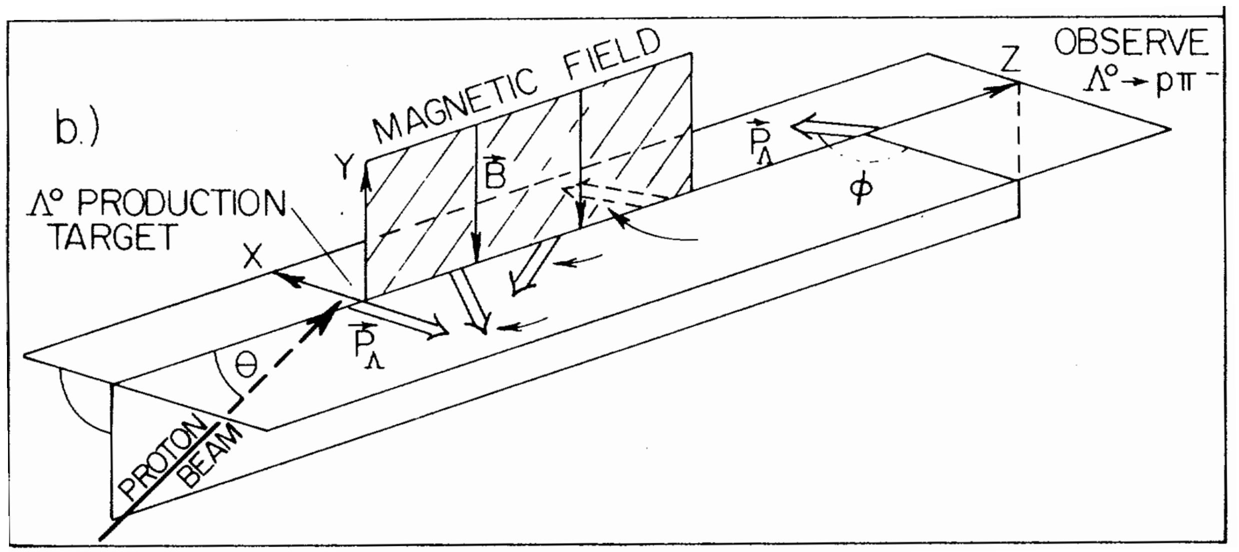
Experimental layout

- Crystal kicker deflects LHC beam halo towards a W target, outside of the LHCb detector acceptance
- Baryons produced in W target and channeled in bent crystal (signal events) enter the detector acceptance



Current Λ baryon EDM limit

- Limit on Λ EDM from E761 fixed-target experiment:
  - Transversal polarization ≈8%
  - Signal yield $3 \cdot 10^6$
  - $\delta_\Lambda < 1.5 \cdot 10^{-16} e$ cm (95% C.L.)
  - $\mu_\Lambda = (-0.613 \pm 0.004)\mu_N$



Phys. Rev. Lett. 41 (1978) 1348

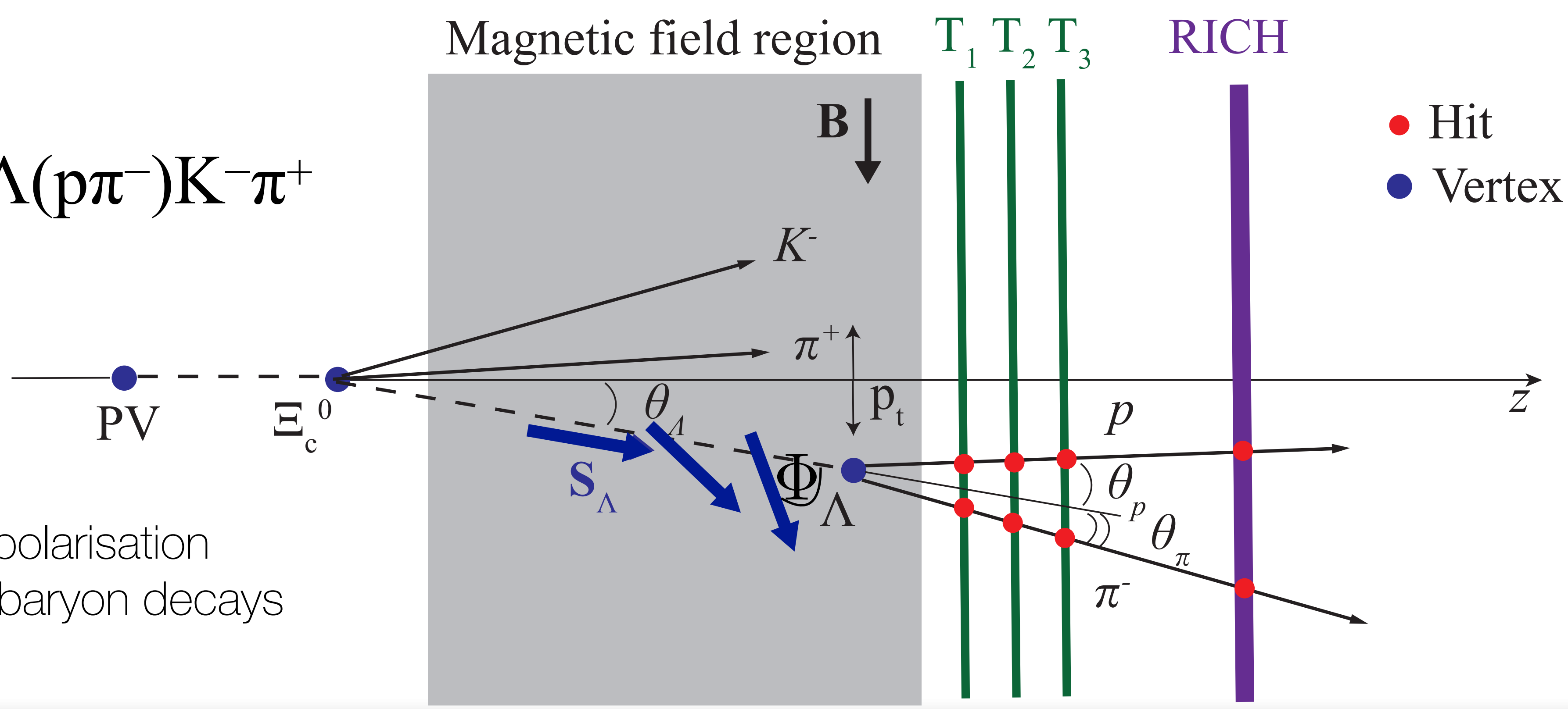
Phys. Rev. D23 (1981) 814

- Experimental setup similar to LHCb, pros/cons:
  - select large sample of Λ baryons from weak charm baryon decays with large longitudinal polarization 😎`(cool)`
  - reconstruction of Λ baryons decaying at the end of the magnetic field region is a challenge 🤓`(nerdy)`

Reconstruction of long-lived Λ baryons

- Reconstruction of Λ baryons at the end of the magnet is challenging: poor momentum and Λ vertex resolution
- Information from T stations and RICH only
- Strategy: use exclusive charm decays, e.g. $\Xi_c^0 \to \Lambda(p\pi^-)K^-\pi^+$ and exploit kinematic constraints
- According to preliminary simulations is doable but requires "ad-hoc" trigger/reconstruction algorithms

$\Xi_c^0 \to \Lambda(p\pi^-)K^-\pi^+$

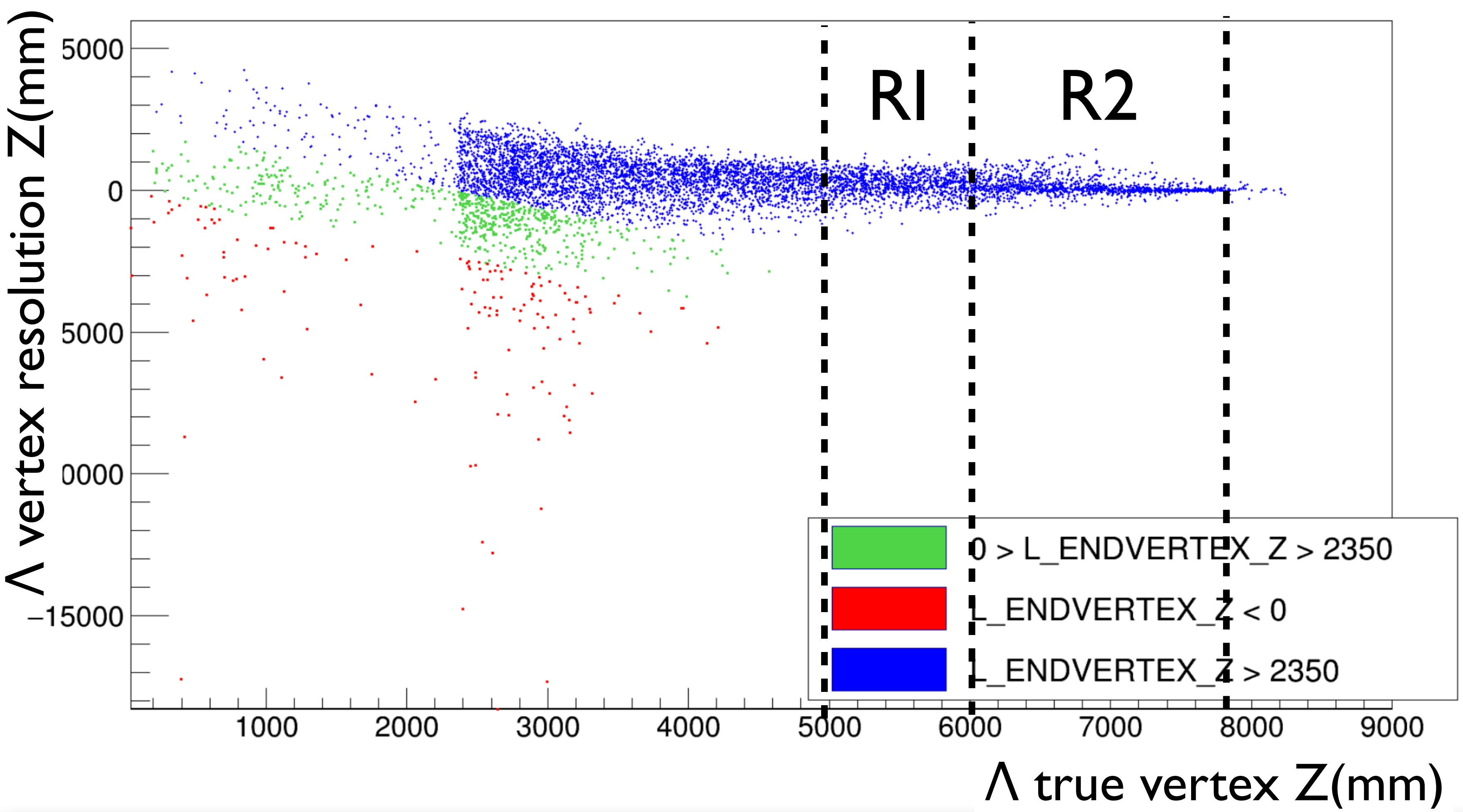


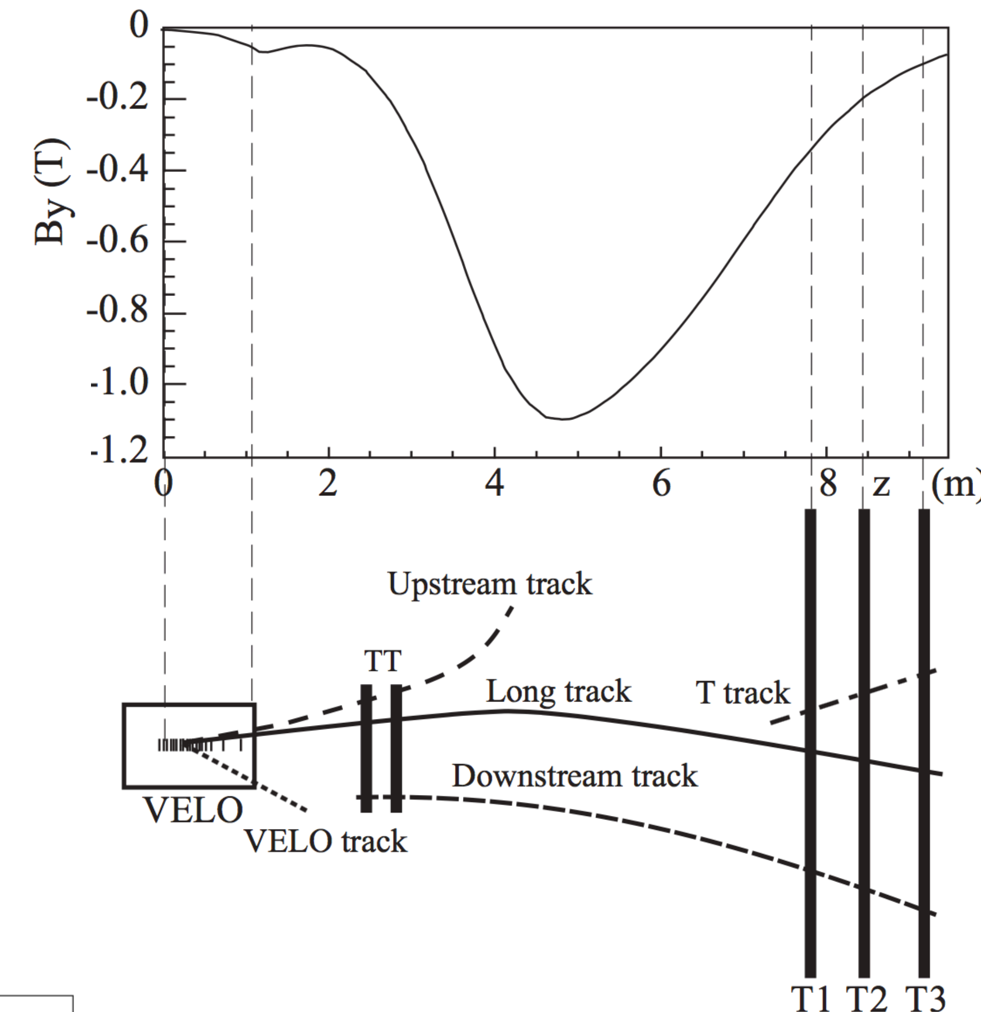
Λ longitudinal polarisation from weak charm baryon decays

Λ baryon vertex resolution

- In R1 vertex z resolution ≈40 cm (40/550≈7%), in R2 ≈30 cm (30/700≈4%)
- vertex x, y resolution ≈2cm

from A. Merli, L. M. Garcia Martin

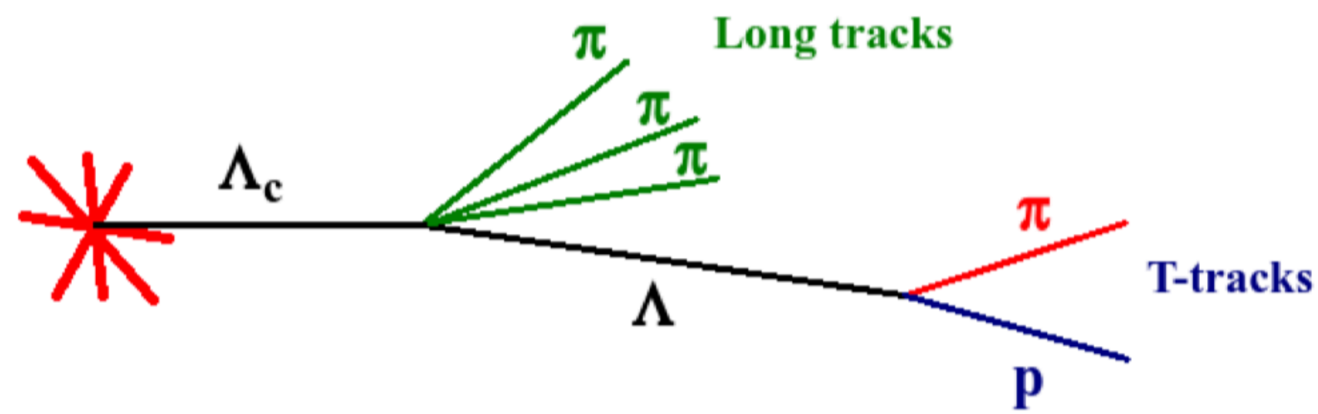


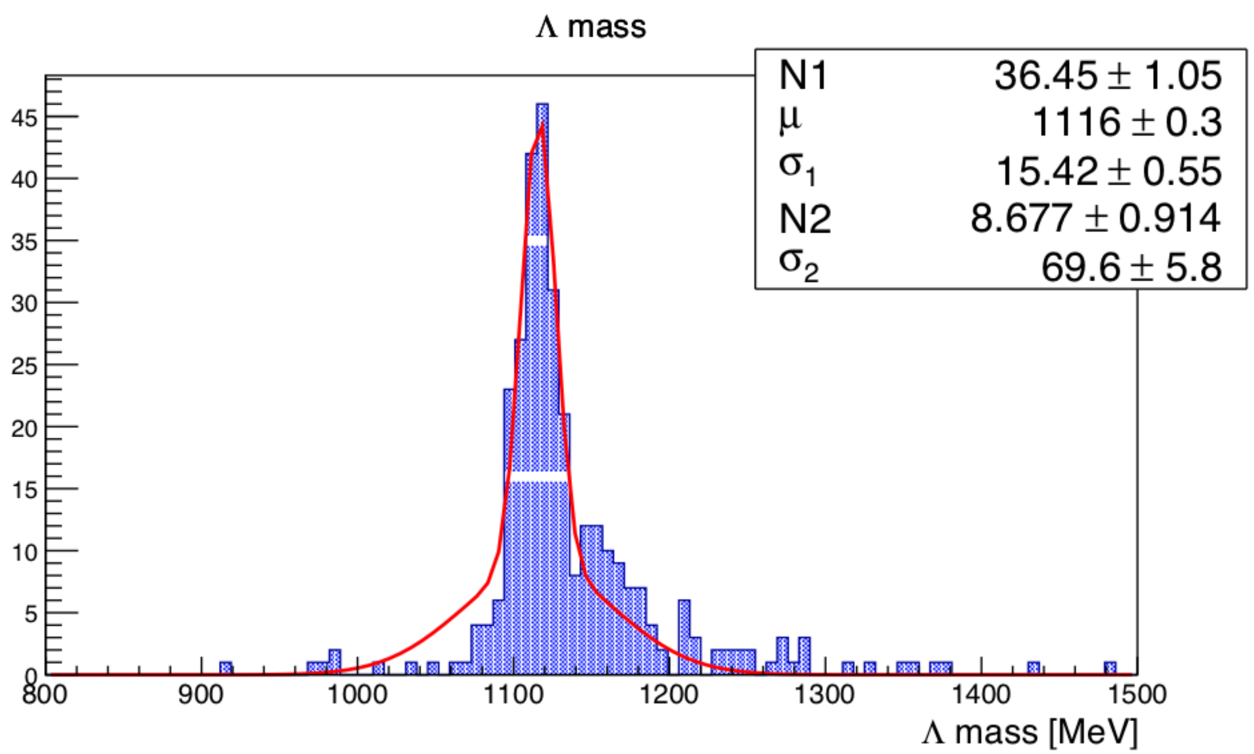


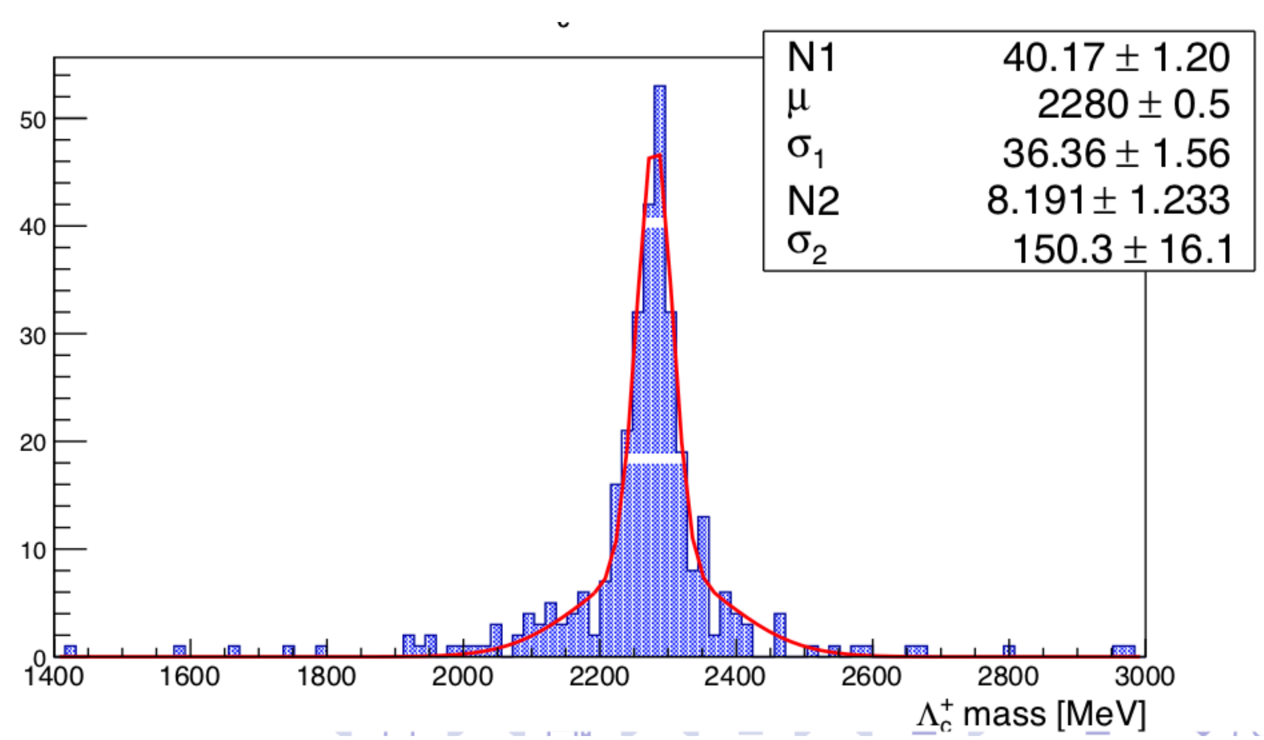
Λ baryon mass resolution

- Use kinematic constraints of entire decay chain

$$\Lambda_c^+ \rightarrow \Lambda\pi^+\pi^+\pi^-$$

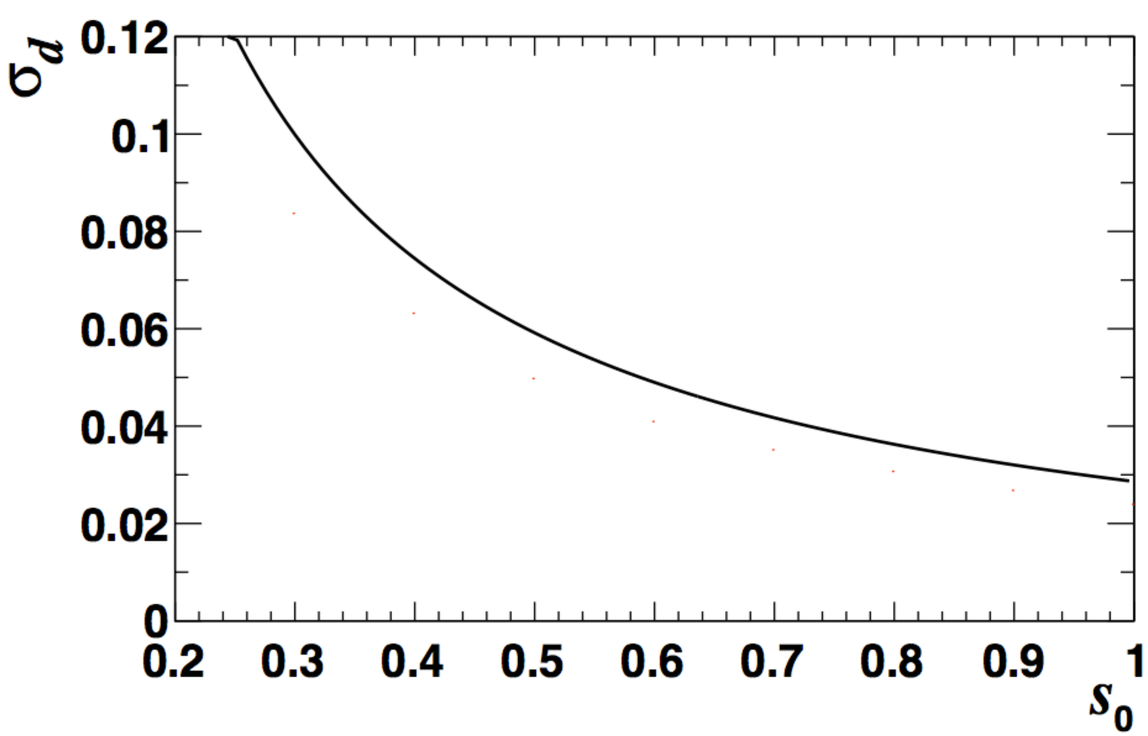


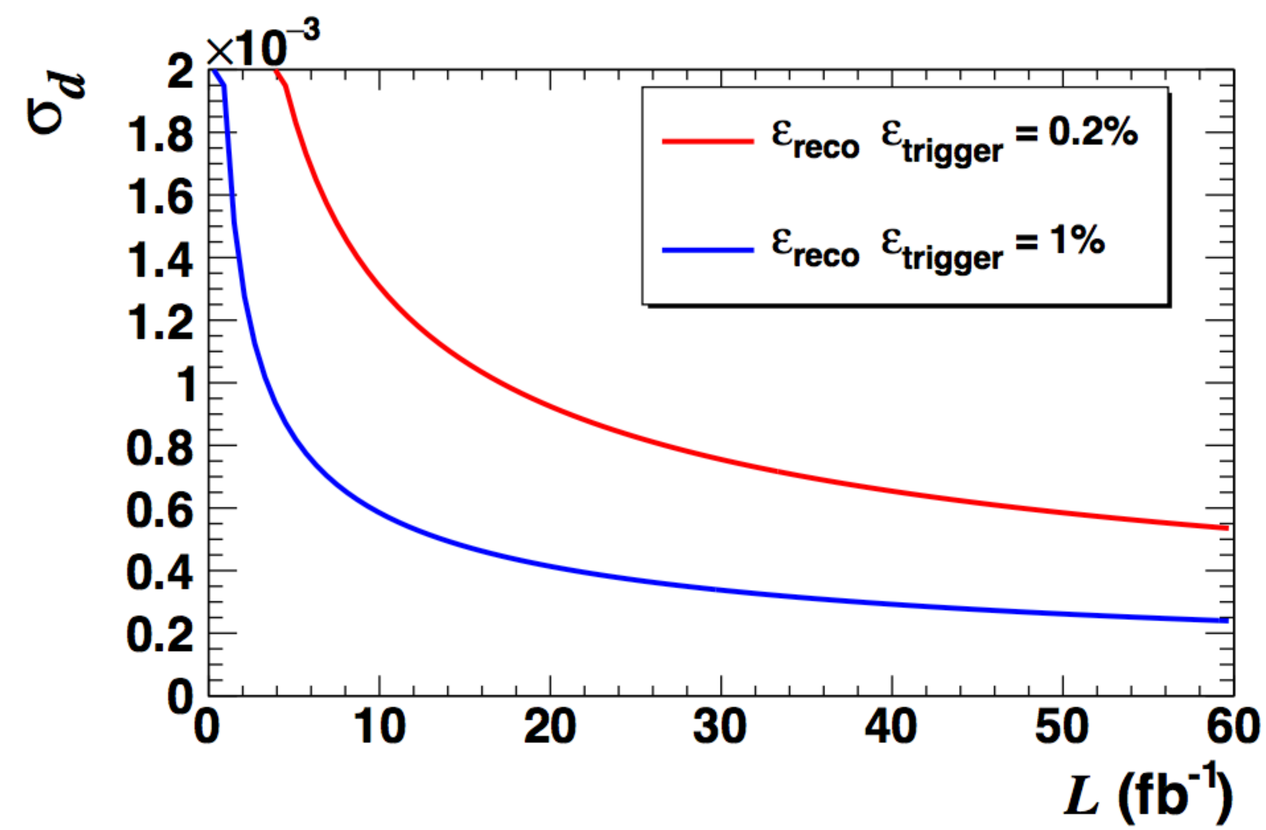




Sensitivity to Λ EDM

- Uncertainty ∝ $1/(S_0\sqrt{N})$, S_0=initial polarization
- Sensitivity to EDM at LHCb. Considering only events from *pp* collisions at ≈14 TeV





- Can achieve 2 orders of magnitude improved sensitivity
- Λ and anti-Λ baryon MDM provide a test of *CPT* symmetry at per-mille level